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NOTES ON STRESS, STRAIN, AND JOINTS

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ABSTRACT

Patterns composed of two sets of slip joints are useful to the geologist as a record from which to interpret the state of stress or strain in the observed rock mass at the time of its failure. For such an interpretation it is necessary to decide whether the direction of greatest compressive stress, or of greatest shortening, be taken as the bisectrix of the acute, or that of the obtuse angle between the joints. Theoretical considerations of failure by slipping along two sets of planes at approximately 90° to one another bring out two general theories. One, called the "stress theory" in this paper, concludes that these planes form acute angles facing the direction of greatest compression; and the other, called the "strain theory," that these planes form obtuse angles facing the direction of greatest compression. An analysis of experimental data and field evidence in the light of the factors evaluated by these two theories suggests the following rule: that in incompetent beds the strain theory be used, i.e., that the direction of greatest shortening be interpreted as bisecting the obtuse angle between the slip joints, and that the joint patterns in competent rocks be used with caution in this connection.

Some remarks on the nomenclature of joints are added, suggesting that joints be classified as "slip" or "rip joints" instead of as "shear" (compression) or "tension joints." Also the general relations of stress and strain are discussed, emphasizing the distinction between causal and internal stresses and the fact that some independent evidence is necessary in order to determine the causal stress from the internal stress or strain condition recorded by the rock structures.

INTRODUCTION

Joint patterns are valuable to geologists in a number of ways, among which is their usefulness as a record from which to interpret rock stress and strain. In this connection the writer has encountered from classes in structural geology many questions which do not seem to have been answered in the literature, and these notes are an attempt to put on a clearer basis some of the problems involved.

More specifically, the writer intends to analyze the inferences as to stress and strain that can be made from a pattern of slip joints, such as fracture cleavage; to discuss the nomenclature of joints; and to point out some of the complications that arise in geologic treatments of stress. In addition, as such considerations require some knowledge of the fundamental mechanical principles, and especially of the factors evaluated by certain generalizations applied to geology, the paper will begin with an effort to put in simple language the essential concepts of mechanical analysis which are involved.

MECHANICAL PRINCIPLES OF STRESS AND STRAIN

The main object of this part is to give the geologist an understanding of the bases on which are built certain generalizations which he uses. Mathematics is eliminated as much as possible, but it is hoped that enough cases are treated by methods that are largely graphical to convince the reader of the truth of the principal conclusions given. The works on this subject that the writer has consulted most are given below,[1] and the reader is referred to them, or to other sources named by them, for such rigorous proofs as he may desire.

STRESS

The term "stress" is used in several ways. It may denote the pair of forces which two bodies in contact exert on each other or only one of these forces, as, for example, the force tending to deform a rock. It is also used to mean the pair of internal forces between two adjacent portions of a body or only one of the forces. The intensity of stress is given in terms of one of the forces per unit area. Often the word "stress" is used alone to mean stress intensity, as in speaking of planes of maximum shearing stress. The significance intended for the term is usually clear from the context in any specific case, but in general statements the variable usage may prove confusing.

The internal stress between two adjoining portions of a body separated by any chosen plane may be conveniently expressed in

[1] G. F. Becker, "Finite Homogeneous Strain, Flow and Rupture of Rocks," *Bull. Geol. Soc. Amer.*, Vol. IV, pp. 13–90; L. M. Hoskins, "Flow and Fracture of Rocks as Related to Structure," *Sixteenth Ann. Rept., U.S. Geol. Survey*, Part I (1896), pp. 845–74; E. R. Maurer and M. O. Withey, *Strength of Materials* (John Wiley & Sons, Inc., 1925); S. Timoshenko and J. M. Lessells, *Applied Elasticity* (W.T.N.S. Press, 1925).

terms of the tangential and the normal component stresses on this plane. Figure 1 shows a section of a unit cube compressed by a downward force P, and held from moving by an equal and opposite force such as might be furnished by a support. Suppose the cube to be divided by some plane normal to the section, shown by the trace EF. The stress which the upper portion of the cube exerts on the lower portion is resolved into the normal and tangential components, N and T. The area of the plane is shown graphically by EF, and hence the intensity of the tangential stress along this plane is $T \div EF$, which may be put in terms of P as $P \cos \theta \div 1/\sin \theta$, or $P \sin \theta \cos \theta$, or $(P \sin 2\theta) \div 2$. Where the plane chosen is such that $\theta = 45°$, the tangential stress is $P \div 2$, which is the maximum value for T. That is, the planes at 45° to the applied compressional stress have the maximum tangential stress. By a similar calculation it may be shown that any plane normal to the applied stress has the maximum normal stress of intensity P.

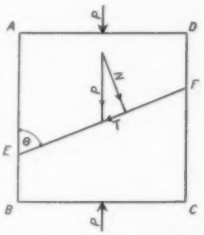


FIG. 1.—The resolution of forces in simple compression.

As a second case, let the unit cube be subjected to compressional and tensional forces of equal intensities, P, acting normal to two pairs of faces. On any plane in the cube the normal and tangential components due to each stress, or pair of forces, may be calculated as above, and by combining these components the total normal and tangential component stresses due to both applied stresses can be found. In this way it may be shown that any plane which is at 45° to both of the applied stresses has the maximum tangential stress of intensity $P/2 \div P/2$, or P. Any plane normal to the compressional stress applied to the cube has the maximum normal compressional stress, which is of intensity P, and any plane normal to the tensional stress has the maximum normal tensional stress, which is of like intensity.

For comparison, the next case considered is that of a simple shear on a unit cube, a section parallel to the forces being shown by Figure 2. By resolving the forces it may be shown that planes normal to the paper and parallel to AD and DC have the maximum tangen-

tial stress, of intensity P, and a plane parallel to AC or BD has the maximum normal stress intensity, which is compressional for BD and tensional for AC, and is equal in intensity to the applied shear, P.

A comparison of the last two cases is made in Figures 3 and 4, which show sections of two large cubical bodies, one of which is subjected to a simple shear stress and the other to a combination of simple compression and tension, all the forces acting parallel to the paper. From what has been written it is clear that the stress condition on the unit cube $ABCD$, of Figure 3, is the same as on that of

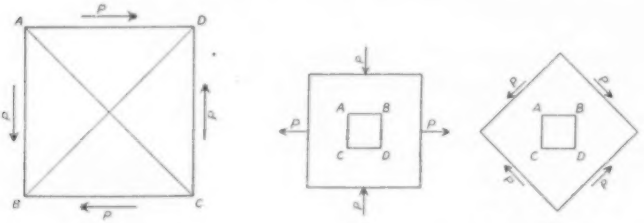


FIG. 2 FIG. 3 FIG. 4

FIG. 2.—A case of simple shear.

FIGS. 3 and 4.—The internal stress condition is the same, whether the applied stress is the combination of simple tension and compression shown or the simple shear.

Figure 4; for example, there is the same maximum intensity of tangential stress along planes normal to the paper and parallel to AD in each.

The general stress condition of either unit cube, $ABCD$, can accordingly be expressed in terms of two stresses, or pairs of forces, acting normal to the two pairs of faces shown by the outlines of the cubes. Conventionally, these stresses are named P_x and P_z, and a negative value is assigned to tensional stress. Then the intensity of the maximum tangential stress, along planes which are at 45° to P_x and P_z, and thus normal to the paper, may be expressed as $(P_x - P_z) \div 2$. Any third stress, or pair of forces, P_y, acting normal to the third pair of faces of either cube, that is, normal to the paper, would have no tangential component on any plane parallel to it, and consequently would not affect the expression given above. Using a similar argument illustrated by a section normal to P_z, and thus parallel to P_x

and P_y, it could be shown that, of the planes normal to this section and hence parallel to P_z, the one at 45° to P_x and P_y has the maximum tangential stress of intensity $(P_x - P_y) \div 2$. As these stresses have been named according to the common usage which makes P_x the stress of greatest intensity and P_z that of least intensity, having proper regard for sign, it is clear that $(P_x - P_z) \div 2$ is greater than $(P_x - P_y) \div 2$, and it may be shown that it is the maximum value for the tangential stress intensities found along all planes in the cube. Applying this statement to the cases shown by Figures 3 and 4, we note that $P_x = P$, $P_y = 0$, and $P_z = (-P)$, so that the value for the maximum tangential stress is $(P_x - P_z) \div 2$, or $(P - [P]) \div 2$, or P.

In order to avoid prolonging this part of the paper, the writer will pass on to certain principles and definitions which, it is hoped, have been sufficiently introduced by the simple illustrations given. The first principle is that any stress condition at a given point in a body can be represented by stresses along three certain axes at right angles to one another. These are called the "principal stresses" and "principal axes," respectively, and the planes formed by the principal axes are called the "principal planes." The principal planes have only normal stresses acting on them, and the intensities of these normal stresses include the maximum and the minimum for all planes that may be passed through the point. The planes which are parallel to the principal axis of intermediate stress and bisect the angle between the other two axes have the tangential stresses of maximum intensity.

The relations outlined may be shown graphically by means of the diagrams of Mohr. In these, horizontal distances to the left of the intersection of the reference lines show intensities of normal compressional stress, and distances to the right show intensities of normal tensional stress. This means that, as used here, measurements to the left are positive; to the right, negative. Vertical distances from the reference point show intensities of tangential stress, regarding whose sign we need not be concerned. In Figure 5 the diagram is given for a simple compression of intensity OA, a case such as that illustrated by Figure 1. The co-ordinates of the points forming the circle give the intensities of the normal and tangential stresses on any plane in the body. For example, DF is the tangential

stress and OF the normal compressional normal stress on a plane making an angle of θ with the direction of the applied stress. Figure 6 gives the diagram for a simple shear, which is the equivalent of a simple compression OA, and tension OB, acting at right angles to one another. A plane at an angle of θ (less than 45°) with the direction of the greatest principal stress, which is the compression of intensity OA, and parallel to the intermediate principal stress, whose intensity is equal to zero, has a tangential stress of intensity DF and a normal tensional stress of intensity OF. Figure 7 shows the solution of the general case of three mutually perpendicular stresses, P_x, P_y,

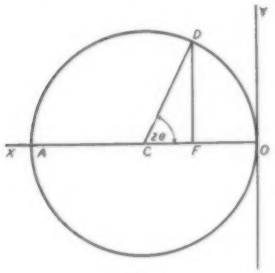


FIG. 5

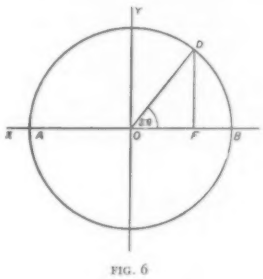


FIG. 6

FIG. 5.—Mohr's diagram for simple compression

FIG. 6.—Mohr's diagram for simple shear

and P_z, represented by OA, OB, and OC. A point D has co-ordinates which give the tangential and compressive stresses on a plane making an angle of θ with the direction of P_y and parallel to P_x. Similarly, points on the large circle, such as P, indicate the stresses on planes parallel to P_y and inclined to P_x and P_z, and K gives the stresses for a certain plane parallel to P_z and inclined to P_x and P_y. The co-ordinates of points in the shaded area show the tangential and normal stress intensities for planes inclined to all three principal axes. It is clear that the maximum intensity of tangential stress is on a plane parallel to the intermediate stress axis and inclined at 45° to the other two.

STRESS AND THEORIES OF STRENGTH

Where the stresses are simple the designer of machines or structures has little difficulty in arriving at the theoretical proportions of

the members to be used, as the necessary data may be secured by direct simple experiments. But for the general state of stress, simple tests no longer yield the required information, and some assumption as to the facts underlying failure is necessary. For this reason various theories of strength have been put forth, which are of interest to the geologist.

The simplest theory is that failure will occur when one of the principal stresses exceeds the limiting strength of the material for simple compression or tension. Whereas this is apparently a satisfactory rule for certain structural materials, the well-known fact that substances can withstand hydrostatic pressures greatly in excess of their simple breaking-stress values eliminates it as a basis of general application.

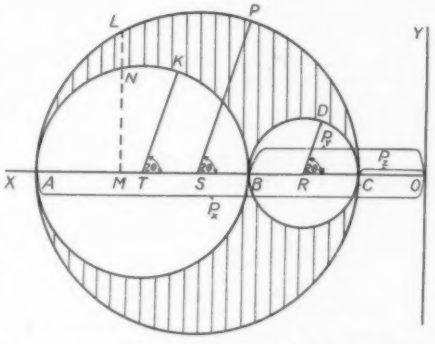


FIG. 7.—Mohr's diagram for the general state of stress.

Where tension and compression act on a body, the tangential components of each are added along certain planes, and failure[1] by shear might occur with neither of the applied stresses near the limit which the material would withstand if the stresses acted separately. This consideration is of particular importance in dealing with materials that yield by shear to simple tension, and forms the basis for the maximum shear theory, which holds that a substance will fail when the intensity of the maximum tangential stress exceeds a certain limit, that is, using the same symbols for the general case as

[1] Engineers distinguish between "yielding" and "failure." For example, a steel bar under increasing tension shows first a sudden deformation accompanied by slipping along certain inclined planes, which marks the "yield point" (the limit of proportional elastic strain). With increasing tension the later "ultimate failure" occurs, usually through a transverse break or rip in the bar. But the word "failure" is used here in its broad geologic meaning, and includes the deformation at the so-called "yield point"; in fact, this is the only kind of failure in steels used for illustrations in this paper.

before, when $(P_x - P_z) \div 2$ is greater than the shearing strength of the material. This theory is in good coincidence with experimental facts on ductile materials. However, it takes no account of possible differences of strength along various planes in the body, a factor which is evaluated by Mohr's theory.

Mohr's theory relates failure by shear to both the normal and tangential stresses in a body. Of the infinite number of planes with the same normal stress than can be traced through a point in a stressed body, the weakest is taken as that with the greatest tangential stress. Referring to Figure 7, all planes with a normal stress

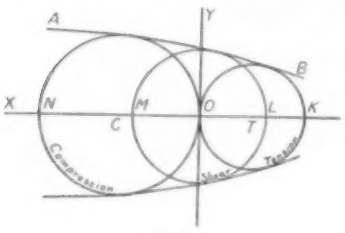
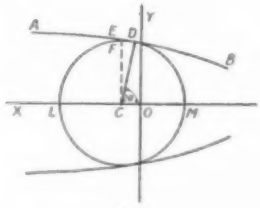


FIG. 8



F.G. 9

FIG. 8.—General diagram for Mohr's theory of strength

FIG.9.—One of the possible limiting states of stress in Fig. 8

equal to OM have tangential stresses varying from MN to ML, and the weakest is the one corresponding to the point L, which represents a plane parallel to the intermediate stress axis.

The intermediate principal stress may therefore be eliminated, and the general diagram for the Mohr theory drawn as in Figure 8. AB is the enveloping curve for all possible circles representing different combinations of the greatest and least principal stresses which cause failure. Three circles are given to illustrate how this curve is drawn. OK, the diameter of one circle, represents the maximum intensity of simple tension the material will withstand, and ON the limiting strength for simple compression. (The assumed material is stronger under compression than under tension.) OL is the greatest intensity of simple shear it will endure without failure. This is the equivalent of a combination of a simple tension of OL and a compression of OM, as has been noted before.

Every circle tangent to the envelope AB gives one of the possible limiting states of stress, that is, a combination of greatest and least principal stresses that causes failure. For example, Figure 9 shows one case where the greatest principal stress is a compression of OL and the least is a tension of OM. The co-ordinates of the point of tangency, D, give the intensities of the tangential and normal stresses on the plane of failure, which makes an angle of θ with the direction of the greatest principal stress. The maximum tangential stress is of course on the plane at 45° to this axis, and is shown by CF. The body, however, will not fail along this plane because, with the normal stress OC, it is able to withstand a tangential stress of CE. It is clear that the plane of failure will be at an angle of less than 45° to the greatest stress axis for any material giving an envelope of the general shape shown, that is, one that fails by shear and has a smaller strength under simple tension than under simple compression.

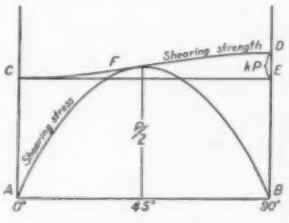


FIG. 10.—The shearing stress and shearing strength plotted (theoretically) for a case of simple compression.

Various other theories have been developed to give the same general results as that of Mohr, and all attempt some evaluation of the modifications of shearing strength under different combinations of the principal stresses. Possibly the nature of the assumptions involved is best demonstrated by the following analysis.

In the case of simple compression shown by Figure 1, the intensity of the tangential stress on planes making an angle of θ with the applied force goes through a maximum when θ is 45°, and the normal stress intensity changes from O to P as θ increases. We will assume the shearing strength along any plane to be a function of the normal compressional stress on that plane, so that the increase in shearing strength is some constant, k, multiplied by the normal stress. The shearing strength may then be plotted against θ as shown in Figure 10, where AC is what might be called the "simple shearing strength," that is, the shearing strength on a plane having no normal stress. On the same base the intensity of the tangential stress is plotted for

an applied stress that causes failure by shear, that is, one of the planes has a tangential stress just exceeding its strength. The figure shows that this plane, corresponding to the point of tangency, F, is at less than 45° to the applied force, and it is clear that, regardless of the exact relation between shearing strength and normal stress on any plane, the general result will be the same as long as the normal compressional stress is assumed to increase the shearing strength.

Taking simple tension as an example, we may similarly plot the decreases in shearing strength due to normal tensional stresses. The indicated plane of failure would then be at an angle greater than 45° to the applied force. However, both cases are covered under the general statement that the planes of failure are at less than 45° to the greatest axis of stress, again giving a negative value to tension. The similarity of this conclusion to that derived from Mohr's theory is apparent, and it will be noted that the principles involved are much the same in each theory.

STRAIN

All stressed bodies undergo a change in shape or size, or both, which is called "strain." The strain is homogeneous when all original units exhibit the same relative strain. It may be shown that any homogeneous strain is the equivalent of three simple strains along certain axes at right angles to one another called the "principal axes of strain." Also, in determining the planes of maximum shearing strain, it is only necessary to consider the section at right angles to the intermediate strain axis, which is the section showing the greatest and least strain. This statement, of course, requires that some account be taken of sign, so that shortening has a sign opposite to that of elongation.

Two cases of strain will now be given to illustrate the statements made. Each shows the deformation of a circular section of an original sphere into an ellipse which is a section of the strain ellipsoid parallel to the axes of greatest and least strain.

In Figure 11 the strain is a simple shear. The point P moves to Q so that $PQ = PR \tan 30°$; K to L so that $KL = KM \tan 30°$; and so on for every point of the original circle. Of course, any angle might have been chosen in place of 30°, but this value is related to the spe-

cific ones used in Figure 12 so as to illustrate a certain principle, as will soon be apparent. Figure 12 shows a combination of two simple strains at right angles to each other. Point P moves to Q so that $QT = \frac{3}{4}\ PR$ and $TO = \frac{4}{3}\ RO$; K to L so that $LH = \frac{3}{4}\ KM$ and $HO = \frac{4}{3}\ MO$; and so on.

Letting $2r$ be the diameter of the circle in Figure 12, then $QT = \frac{3}{2}\ r$ and $GL = \frac{8}{3}\ r$. Hence the area of the ellipse, which is $\frac{\pi}{4}\ QT \cdot LG$, reducing to πr^2, is equal to that of the original circle. With simple shear strain, as shown in Figure 11, the area of the

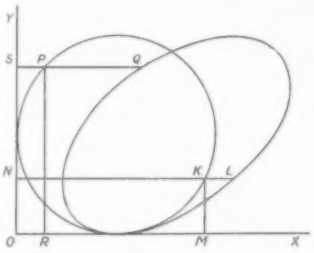


FIG. 11

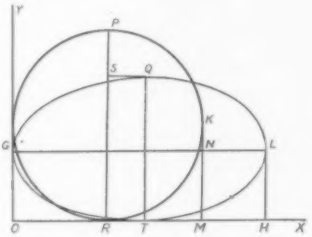


FIG. 12

FIG. 11.—A section showing the deformation of a sphere into an ellipsoid by simple shear.

FIG. 12.—A section showing the deformation of a sphere into an ellipsoid by a combination of simple elongation and shortening.

ellipse must evidently be the same as that of the circle. A comparison of Figures 11 and 12 will show that the strains have been chosen so that the circle and ellipse of one drawing are practically identical with those of the other.

These examples are probably sufficient to show that any simple shear strain is the equivalent of a certain combination of shortening and elongation at right angles to one another. In short, the principle illustrated is that any homogeneous strain may be expressed in terms of three simple strains at right angles to one another, and we may proceed with the confidence that any generalization based on this statement of a strain covers shear strain as well.

The next step will be to consider the intensity of the shearing strain along various planes in a strained body. In Figure 13 only a

quadrant of the original circle is shown. The reference lines intersect at the center of the circle, and the strain is the same as in Figure 12. Four small squares are drawn in their original and their deformed shapes so as to give a picture of the shearing strain along the planes normal to the paper shown by the lines *UO*, *VO*, *PO*, and *WO*.[1] More definitely it is noted that the three points *K*, *L*, and *M*, which form a right angle in the original circle, move to *N*, *R*, and *P*, where they no longer form a right angle. During the strain the point *M* gradually approaches the line *KL*, and also moves tangentially with respect to it, until, at the final stage shown, it has accumulated a tangential movement of *PQ* with respect to the line *NR*.

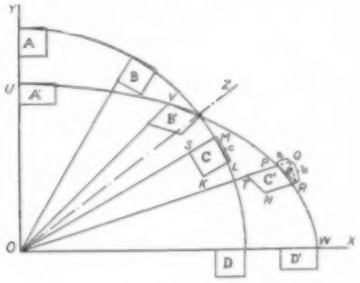


FIG. 13.—A section showing the intensity of the shearing strain along various planes in an ellipsoid made by the deformation of an original sphere.

In engineering practice, strains are measured in terms of the original dimension. On this basis, the shearing strain along the plane *PO* would be $a \div c$. If measured in terms of the final dimension, it would be $a \div b$, which is equal to tan θ.

By adopting the first basis it may be shown that the maximum shearing strain is along the plane which is normal to the paper and has the trace *OZ*, which joins the intersection of the circle and the ellipse with reference point *O*. The strain along the intermediate axis normal to the paper is nil, so that the plane shown by *OZ*, which is parallel to this axis, is a plane that has not been distorted by the strain. The generalization is therefore made that for simple shear, the planes of no distortion are the planes of maximum shearing strain. (There would, of course, be another plane similar to *OZ* in the northwest and southeast quadrants, which are not shown.) It may be worth while repeating that this applies only to simple shear strain, as the generalization has been applied to strain where a change of volume occurs.

[1] For this graphical method the writer is indebted to Professor Maurer, of the Mechanics Department of the University of Wisconsin.

By using $a \div b$ as a measure of the shearing strain, it is possible to develop in a fairly easy way a statement that covers all kinds of homogeneous strain. The method follows in full, as, to the writer's knowledge, it has not been used before. The position of the points which form the right angle in the original circle is evidently a matter of choice. Thus, it is possible to use a simpler drawing than the previous one, as shown by Figure 14, which eliminates a considerable amount of mathematics in determining the variation in the angle θ for different orientations of the three original points. These are chosen as O, at the intersection of the two reference lines; M, a random point of co-ordinates a, $a \tan \alpha$; and E, on one reference line so that OME is a right angle, that is, the co-ordinate of E is $a + a \tan^2 \alpha$.

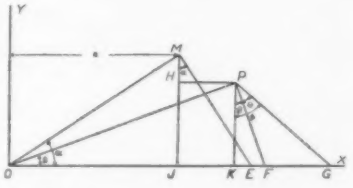


FIG. 14.—The construction used for determining the plane of maximum shearing strain.

After the strain, M is at P, so that $OK = 4a \div 3$, and $PK = 3a \tan \alpha \div 4$, using the same unit strains as before. Similarly, the point E is at G, so that $OG = 4(a + a \tan^2 \alpha) \div 3$. The angle θ, which is the difference between the angle OPG and the right angle OPF, may then be found as follows:

$$KG = OG - OK = \frac{4(a + a \tan^2 \alpha)}{3} - \frac{4a}{3} = \frac{4a \tan^2 \alpha}{3}$$

$$\tan \phi = \frac{KG}{KP} = \frac{4a \tan^2 \alpha}{3} \cdot \frac{4}{3a \tan \alpha} = \frac{16}{9} \tan \alpha$$

$$\tan \beta = \frac{KP}{KO} = \frac{3a \tan \alpha}{4} \cdot \frac{3}{4a} = \frac{9}{16} \tan \alpha$$

$$\theta = \phi - \beta = \tan^{-1}\left(\frac{16}{9} \tan \alpha\right) - \tan^{-1}\left(\frac{9}{16} \tan \alpha\right).$$

The maximum for θ as given by the final equation, and therefore the maximum for $\tan \theta$ as well, corresponds to a value of 45° for α.

The equation may now be modified to cover the general case of any homogeneous strain expressed in terms of three simple strains at right angles to one another. We need consider only the greatest

and least strain, having due regard for sign by giving a negative value to shortening. These, in terms of strains per unit of original length, called "unit strains," will be denoted by s and e. For example, in the case shown by Figure 14, the greatest shortening, s, is $(-\frac{1}{4})$, so that PK may be expressed as $(1+s)\,a \tan \alpha$, or $(1-0.25)a \tan \alpha$. α again is the angle which a plane parallel to the intermediate principal axis makes with the direction of greatest elongation. The general equation is then:

$$\theta = \tan^{-1}\left(\frac{1+e}{1+s}\tan\alpha\right) - \tan^{-1}\left(\frac{1+s}{1+e}\tan\alpha\right).$$

When $e=s$, that is, for equal shortening or elongation along the three principal axes, since the intermediate strain must also be equal to e or s, the equation gives a value for θ of zero. In other words, there is no shearing strain in simple dilation. For all other cases, θ is a maximum when $\alpha = 45°$.

In the general case, the greatest shearing strain is therefore along the plane parallel to the intermediate axis of strain and originally at 45° to the other two axes. It is clear that, after the strain, this plane will be at more than 45° to the direction of greatest relative shortening, that is, to the shortest axis of the strain ellipsoid, and that, the greater the deformation of the ellipsoid, the more the angle between this plane and its symmetrically disposed equivalent will vary from 90°. For small strains, such as are ordinarily obtained in tests of structural materials, the planes will be practically at 45° to the shortest axis of the strain ellipsoid.

The question of which of the two bases of measuring shearing strain should be used now presents itself. But this will not be discussed, because the writer believes it is not of essential importance to the geologist. Even for the large strain shown by the drawings, there is an angle of only 8° between the plane of maximum shear determined by one method and that found by the other. Both show the obtuse angle between the indicated planes of failure facing the shortest axis of the strain ellipsoid, and the main problem of geologic interest is how the somewhat contradictory conclusions from stress and strain are to be applied to rocks.

The writer may here be permitted to interpose the opinion that

the generalization he has developed for the position of the planes of maximum shearing strain is more serviceable than the other. That is, by using $a \div b$ as a measure, it is clear that these planes will always be at an angle of 45° or more to the direction of greatest shortening, regardless of the unit strains. The other generalization, however, has been extended to imply that, with a volume increase, this angle would be less than 45°. But, for example, by analyzing a strain represented by an ellipsoid which has its longest axis 1.3 times the diameter of the original sphere, its shortest axis 0.9 times this diameter and its intermediate axis the same as this diameter, it is found that the planes of maximum shearing strain measured by $a \div b$ and those measured by $a \div c$ are all at more than 45° to the direction of greatest shortening, there being an angle of about 5° between the planes derived from one method and those from the other. The plane of no distortion is at less than 45° to the direction of greatest shortening. In short, the main result is apparent from one generalization but not from the other.

DISCUSSION OF STRESS AND STRAIN

Before going on it may be well to review the salient features developed above. By considering shearing failure as a function of both the normal and the tangential stresses along various planes in a stressed body, the conclusion is reached that failure should occur along two planes parallel to the intermediate stress axis and forming an acute angle bisected by the greatest stress axis. This statement will hereafter be referred to as the "stress theory." From an analysis of strain, on the other hand, the indication is that failure by shear should occur on two planes parallel to the intermediate strain axis and forming an obtuse angle toward the shortest axis of the strain ellipsoid. This statement will be called the "strain theory."

Strain is not directly involved in the development of the stress theory. However, as forcibly shown by the fact that a simple compression causes some materials to split parallel to the applied force, the effect of internal stresses due to strain must be taken into account in any analysis of the general state of stress in a body, which requires knowledge of the relations between stress and strain.

Within a certain limit almost every substance shows a ratio be-

tween stress and strain which is characteristic for that substance. For example, a bar of soft steel subjected to longitudinal compression below a certain maximum shows a shortening per unit length which is in direct proportion to the intensity of the compression, and at the same time its cross-sectional dimensions show unit increases which vary directly with the longitudinal unit strain. If the stress is removed, the bar will return to its original shape, that is, the applied force sets up internal reacting stresses. The nature of these internal stresses is inferred from experimental data on stress and strain, and the stress condition as determined forms the basis for the mathematical analysis of structures. If the stress on the bar is increased to the limit mentioned, failure (or yielding) occurs, and the bar becomes appreciably shorter while the applied stress actually decreases. A graph of the relations between stress and strain accordingly shows a marked change corresponding to this condition, at a point technically called the "yield point." The failure is shown by lines on the bar which are known as "Lueders' lines." These mark planes at approximately 45° to the axis of the bar, and indicate failure by slipping along these planes.

The material taken as an example exhibits definite relations of stress to strain up to the yield point, making possible a complete statement of the stress condition at the time of failure. However, present purposes require only the qualitative statement that the greatest stress axis is parallel to the applied force. The stress theory would therefore prophesy failure by shear along planes at less than 45° to the axis of the bar.

The strain condition may also be completely solved for the given case, but again only a simple statement is necessary here, to the effect that the axis of greatest shortening is parallel to the longest dimension of the bar. Thus the application of the strain theory would prophesy failure by shear on planes at more than 45° on the shortest axis of the strain ellipsoid, which coincides with the axis of the bar.

This case has been taken to show that the application of the two theories to the same case gives contradictory results, making it clear that the factors evaluated by each are not the same, or that the same factors are evaluated differently, or both. If we assume that both

theories consider real factors, but that the effect of each factor is modified by the kind of material and the conditions of deformation, we may proceed toward conclusions of some value by comparing the observed facts under known conditions with the results predicted by each theory. For example, in the case given above, the conditions at the time of failure would be those of large stress intensities and small unit strains, and the angles between the slip planes would be acute toward the direction of greatest stress, that is, in accordance with the references from the stress theory. This suggests that wherever such conditions exist, the failure would follow the predictions of the stress theory. The same relations might also be generalized by noting that, since the strain is negligible, determining quantitatively the angles indicated by both theories and averaging them would give a result roughly corresponding to the facts. Geologic examples are more complex, but the same procedure will be adopted in their analysis.

INTERPRETATION OF TWO SETS OF SLIP JOINTS

THE STRESS AND THE STRAIN THEORIES

The mechanical principles that are essential in connection with this problem are summarized here for the benefit of those who have not followed through the preceding part of this paper. Suppose a cube has stresses of different intensities acting normal to its faces, and that the stress on each face is balanced by an equal one on the opposite face, then the two planes in this cube which are parallel to the stress of intermediate intensity and at 45° to the greatest stress are those with the greatest tangential stress. If the shearing strength of the material were the same in all directions, the cube would fail along one of these planes by slipping provided this tangential stress were large enough. But the shearing strength along a plane is greater the larger the normal compressional stress on this plane, and planes at more than 45° to the greatest stress have greater normal compressional stresses than those at less than 45°. Failure will occur where the shearing stress first exceeds the shearing strength, and this condition is present on planes at less than 45°. Such is the argument behind the stress theory, which holds that failure by shear occurs on planes at less than 45° to the direction of greatest stress. It is noteworthy that strain is not primarily involved in the development of

this theory; that is, as long as the stress condition is known, it is immaterial whether the cube has suffered great strain or has been perfectly rigid. Now, if it was known that the cube was the result of the deformation of an original block of a certain size, so that the shortenings or elongations that had occurred in three directions at right angles to one another were known, it would be possible to calculate the position of the planes along which the greatest shearing strain had occurred, and to show that these are at angles of more than 45° to the direction of greatest shortening. On this basis is formulated the strain theory, which holds that failure will occur along those planes at more than 45° to the direction of greatest shortening. It is to be noted that this theory is not concerned with the intensities of the stresses causing the strain.

These theories may be compared by considering the example of a bar of soft steel, which, under simple compression, would show strains proportional to the stress up to a certain limit, at which the bar would fail by slipping along planes at about 45° to the direction of the applied stress. In this case, it is clear that the direction of greatest stress coincides with the direction of greatest shortening, which is the relation of interest in applying the two theories. Consequently, the angle between the slip planes and this direction would be inferred to be less than 45° from the stress theory, and more than 45° from the strain theory. Assuming that real factors are evaluated by both theories, but that the effectiveness of each varies with the conditions of deformation, there remains the task of determining whether or not it is possible to relate the weight to be attached to the predictions of each theory with the conditions of rock deformation.

THE PROBLEM

Patterns which consist of two sets of slip joints (which are also known as "shear" or "compression joints") are in places very valuable as records of internal stress or strain in a rock mass at the time of their formation. Such joints are most simply described in their relations to stress as making angles of about 45° with the directions of greatest pressure and easiest relief. The reader will not need to have it pointed out that it is the variations of the angles from 45° that is of value in interpreting stress or strain from the joint pat-

terns, and that, in general, two theories, the stress and the strain, may be applied to any given case, each indicating a different conclusion.

A theoretical analogy to the problem which the geologist faces in a rock outcrop is given by supposing that it is necessary for someone to determine from an iron bar, that has been deformed to the extent of causing observable slip planes, whether it has been pulled or compressed longitudinally, assuming that one or the other of these causes was the only possible one. The person to whom this task is assigned may note that the slip planes are not at right angles, but form acute angles facing the ends of the bar and obtuse angles facing the sides. If he applies the stress theory, he will conclude that the direction of greatest stress bisects the acute angles, and that therefore the bar was either compressed longitudinally or pulled laterally, the first cause being the only one possible under the conditions of this case. If, on the other hand, he applies the strain theory, he will conclude that the direction of greatest shortening bisects the obtuse angles, and that therefore the bar has been either compressed laterally or pulled longitudinally, the second cause being the only possible one in this case.

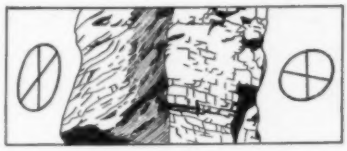


FIG. 15.—Portion of Van Hise rock, on the left limb of the Baraboo syncline. (Sketched from Leith's *Structural Geology*, p. 156.)

The geologist, however, may want a less theoretical example, and one that shows the usefulness of interpreting joint patterns, as well as the difficulties. Such an example is well furnished by Van Hise rock, on the Baraboo syncline of Wisconsin, illustrated by Figure 15. The section is about normal to the strike of all the joints considered, and therefore shows the directions of greatest or least strain or stress. The fracture cleavage in the shaly bed to the left of the figure is considered to represent one set of slip joints, the other being parallel to the bedding. Lines bisecting the obtuse angles shown by the section between these sets are assumed to show the direction of greatest shortening, and those bisecting the acute angles, the direction of greatest elongation of the rock strain causing the fractures. In short,

the strain theory is applied. As the strain is attributed to shear between the beds during folding, it may be used to determine the direction of the movement between the shaly stratum and the adjacent massive quartzite, which in turn leads to conclusions as to the position of the outcrop on the fold and the pitch of the fold (by the divergence from the horizontal which is shown by the intersection of a joint of one set with one of the other). The quartzite to the right of the figure also shows a pattern which is considered to represent two sets of slip joints. In the central part of the figure the joints of one set form with those of the other definite acute angles facing the lower right-hand corner. In this case the direction of greatest shortening is assumed to bisect the acute angles, that is, the stress theory is applied, and this leads to the same general conclusions as given above. The ellipses at the sides of the illustration show the assumed relations between the strains and the joint patterns.

This example shows that the problem resolves itself into a question of which theory to apply to any given case; that is, we must attempt to determine under what conditions the effective factors are best evaluated by the strain theory, under what conditions by the stress theory, and what facts are present in the deformational record to indicate these conditions. The first step is to take up the facts shown by field and experimental evidence.

DATA ON FAILURE ALONG SLIP PLANES

In compression tests of building stones[1] it is found that the unit shortening is not directly proportional to the stress intensity, although the departure from true proportionality is not usually large. A small set is shown for low loads, but the tested pieces are approximately elastic up to their breaking-point, and are accordingly classed as brittle substances. The planes of failure are habitually at less than 45° to the direction of the applied compression. A cone-shaped surface of fracture is common, owing to the special conditions of stress present, namely, the fact that the intermediate and least principal stresses are equal. This feature is merely noted in passing, as it is rare in rock deformation, though common in tests.

In the field rocks are found showing patterns of slip joints which

[1] Johnson, *Materials of Construction*. John Wiley & Sons, Inc., 1925.

commonly have obtuse angles facing the shortest axis of strain, but some cases show acute angles. The general nature of the evidence for this statement is illustrated by Figure 15, and many other examples will no doubt occur to the reader. It is possible, however, to generalize the field evidence by noting that the strain theory has long been used satisfactorily in interpreting fracture cleavage in incompetent beds, and that increases in the obtuseness of the angle between the slip joints have been noted to correspond with increases in the strain.

Experiments on the deformation of rocks under containing pressures cover conditions more or less intermediate between those at the surface and those at depths in the crust of the earth. Excellent summaries of the data available from this source are given by Steidtmann[1] and Bucher.[2] Probably the most interesting of the experiments referred to are those of Karman, which show, with an increase in the confining pressure, a progressively larger angle between the fractures which faces the greatest stress axis. Referring to Figure 9, it will be noted that the shape of the enveloping curve AB is such that the angle θ would have been larger if a limiting stress condition had been chosen so that the least principal stress were greater, always considering tension as negative. The effect would be to shift the tangent circle to the left, making the contact at a point where the slope of AB with regard to OX is less. Karman's data yield an enveloping curve of the same general shape as AB, and therefore Mohr's theory is in agreement with these facts. However, it does not follow that an obtuse angle facing the greatest stress axis could be predicted, because all experimental data give an increasingly large stress difference for failure as the confining pressures are increased, which means that the corresponding Mohr's circles become larger to the left.

Leaving rocks for the moment, it may be noted that Mohr's theory, and also other similar stress theories, explain satisfactorily the variation in the angle shown by Lueders' lines obtained in tension and compression tests of steels, including low-carbon steels

[1] C. K. Leith, *Structural Geology*, pp. 356–83. Henry Holt & Co., 1923.

[2] W. H. Bucher, "The Mechanical Interpretation of Joints," *Jour. Geol.*, Vol. XXVIII, pp. 707–30; Vol. XXIX, pp. 1–28.

which are classed as ductile substances. In fact, the failure along slip planes of all but a few materials, such as clay and soap, is shown by tests to be at an angle of less than 45° to the greatest stress axis.

The writer made a number of tests on the deformation of paraffin, using the method described by Mead.[1] Combinations of shear with shortening were used over the entire range that yielded patterns of slip joints normal to the surface of the sheet, and the experiments were made at temperatures differing considerably. The object was to observe the relation between the strain and the angle between the slip joints. The type of strain used was found to affect distinctly the relative numbers of the kinds of joints formed, the variation being as would be expected, namely, that the failure of the paraffin by splitting increased as the element of simple elongation combined with the shear strain was greater, but no relation was discovered between this factor and the angle formed by the slip joints. This angle, however, was markedly affected by temperature, and was as small as 75°, facing the shortest axis of strain, for the lower temperatures. In all the tests, the strain was continued after the first fractures formed, and the angles were measured between two or three well-formed pairs of slip planes developed at successive stages. These were then corrected for the variation they had undergone owing to the strain since their formation. In eight out of ten cases definite increases of 5°–10° in the angles facing the shortest axis of strain were noted, and in none was there any marked decrease. The paraffin clearly did not conform to either the stress or the strain theory entirely, as angles from 75° to 105° were noted facing the shortest axis of strain.

CONCLUSIONS AS TO THE SOLUTION OF THE PROBLEM

The problem of interpreting internal stress or strain from a pattern of slip joints is essentially one of determining whether or not the record contains any facts indicating conditions of deformation which guide our judgment in regard to the relative weight to be attached to the predictions of the stress and the strain theories. The foregoing data will now be considered with this object in mind.

[1] W. J. Mead, "Notes on the Mechanics of Geologic Structures," *Jour. Geol.*, Vol. XXVIII, pp. 505–23.

A general comparison of the field evidence and the results of ordinary tests on building stones brings out again the ever perplexing difference between the behavior of rocks at the surface and at depths in the earth. The nature of the differences in the conditions for these two cases is partly known, and the extent to which these may be correlated with the observed variation in rock behavior through the two theories is of interest. Rocks show limiting states of stress which may be represented in Mohr's diagram by an enveloping curve concave toward one reference line, as illustrated by *AB* in Figure 9. This indicates that with high confining pressures the effect of the variation in normal stresses is reduced. On the other hand, the fact that hard rocks at depths in the earth have been considerably deformed without rupture certainly suggests the increased influence of shearing strain, which, for small strains such as are shown by hard rocks at the surface, indicates only a negligible departure from 90° for the angle between the planes of failure. The writer's experiments lend some support to this view, as the paraffin at low temperatures broke with very little strain and showed slip joints in accordance with the stress theory, whereas, with increase in strain before rupture, the change in the patterns was as would be inferred from the strain in theory. In short, the mere fact that the joint pattern is in an outcrop composing a part of the crust of the earth indicates conditions different from those of ordinary tests (the elements of time and temperature as well as increased confining pressures entering the situation), and both experience and more or less theoretical considerations suggest that the predictions of the strain theory are to be given more attention in interpreting field evidence than in analyzing the results of simple experiments on rocks. Of course, near-surface deformation is excluded here.

It is clear that this broad generalization can be made more definite for specific cases. The relative intensity of the conditions of rock deformation can be judged in a qualitative way for that portion of the crust under observation. Also in many cases it can be seen that certain smaller portions have undergone more strain than others, and our evidence is such as to show definitely that, as the strain increases, the strain theory can be applied with more and more certainty.

The fact, however, that is shown best by the structural record is

the kind of rock that has suffered the deformation, although even this evidence must be examined with a view toward determining whether the rock was the same at the time of its deformation as it now appears. It is fortunate, then, that the relation between the kind of rock and the angle between the slip joints is fairly definite, in fact, is often such that other considerations may be neglected. At the surface, hard rocks under compression break in accordance with the stress theory, but the failure in clay corresponds with the inferences from the strain theory. In the field, fracture cleavage in shaly beds is also in accordance with the strain theory, but quartzites and granites, on the other hand, commonly show variable angles, even in the same rock mass. If we note that, in general, weak materials which undergo large strains before rupture show slip planes which correspond to the predictions of the strain theory, it is evident that the facts are in accord with what we would expect from a consideration of the factors evaluated by the two theories.

The foregoing discussion shows that any generalization which is to be of help in guiding our judgment of the weight to be attached to the inferences from each theory must cover the type of rock and the conditions of its deformation. The terms "competent" and "incompetent" are widely used in connection with the observed structural characters of rocks, usually in such a way that a weak rock that has undergone considerable deformation is called "incompetent." Moreover, the writer has the impression that these terms have a common implication of relativity, which is particularly valuable for our purpose. The rule is therefore suggested that in incompetent rocks the patterns of slip joints be interpreted in accordance with the strain theory, and that in competent rocks the patterns be used with caution.

The writer realizes that this is a somewhat vague rule, but hopes that it will be of some service, even if only to keep in mind the fact that certain assumptions are behind any interpretation of internal stress or strain based on the angles shown by a pattern of slip joints, and that no simple geometric rule holds for all cases. It may not be out of place to note here that it is often possible to select portions of a rock mass for observation so that the chance of error is greatly diminished; for example, a small incompetent bed between large

competent beds which have been folded forms an ideal case for the application of the strain theory, because the shearing has been accentuated in the weak bed, and the strong beds tend to distribute the strain evenly.

As an example, the rule may be applied to the case of the Baraboo quartzite shown by Figure 15. The strain theory would be applied to the shaly bed because it is a type of rock that is notoriously incompetent. Moreover, it lies between large competent masses of quartzite, so that a uniform stress condition could be assumed, and the chances of error through accepting the inferences derived from one outcrop would be small. As quartzite is known as a very competent rock, the stress theory would probably be applied to the joint pattern in the quartzite of this outcrop if it were necessary to use it. But in this case an interpretation from this source is not required, although the data, measured in terms of the angle formed by the slip joints, on the relative competence of the quartzite under the local conditions of deformation might be recorded for use near by where only the quartzite might be exposed. Among the local conditions to be noted and considered in future applications of the data would be the thickness of the quartzite and the nature and thickness of the adjacent beds. Thus the presence of an adjacent incompetent bed no doubt would relieve the stress on the quartzite somewhat, so that it would be relatively more competent under such a condition than under one where it lay between larger beds of quartzite. However, it will be noted that the quartzite of the illustration shows only a very general pattern, and any conclusions based on it would be accepted only tentatively.

As the primary object of interpreting patterns of slip joints is to determine the local strain or stress, a reminder that associated structures may solve the problem seems in order. From their very nature, slip joints may be expected to show appreciable tangential movement in places, that is, become faults, the displacement of which shows which way the rock has been elongated or shortened, and, as the presence of evidence of this sort is very probable, it should be sought for carefully. Genetically associated flow cleavage, drag folds, small thrust faults, and gash veins from further examples.

Finally, it may be noted that many rocks show marked varia-

tions in their shearing strengths along different planes. The commonest cause of this is stratification, which affects the position of one plane of slipping, and may lead to obscuring its presence altogether. The angle between the slip joints may be changed by this factor, and the direction of greatest shortening may no longer bisect this angle. However, the evaluation of this factor is clearly to be left to the analyses of specific cases.

NOMENCLATURE OF JOINTS

A joint is a fracture in a rock due either to a small slip of one portion of the mass past the other along the break or to a tearing apart of one portion from the other, the movement being normal to the break. The first class are commonly known as "shear" or "compression joints," and the second as "tension joints."

The variable usage of stress terms has already been noted. In mechanical analyses, a stress condition is usually defined in terms of internal stresses, but the geologist, on the other hand, commonly thinks of stress as a force applied to a body. But the present nomenclature of joints involves both usages, and is therefore somewhat confusing. For example, the term "compression joint" clearly refers only to a slip joint caused by external compression of the mass considered, that is, the naming is after the causal stress; whereas the term "shear" (or "tension") "joint" means that the tangential (or normal) stress component on the observed plane caused the fracture, that is, the naming is after the internal stresses.

Owing to the geologic tendency to consider a stress only as a causal force, the fact that either a tension or a shear joint may be the result of either tension, compression, or shear applied to the rock mass often presents a problem to the beginner, and in any case forms a trap that is not always avoided. Furthermore, engineering students, after learning that the planes of maximum shearing stress are always at 45° to the greatest stress axis, find it difficult to reconcile this fact with the geologic precept that a shear joint may form at any angle to the direction of stress (by which is meant "causal stress").

However, the writer's main objection is not that these little difficulties arise, but that the present terms are often taken to mean more than the simple facts of the case. For example, a student is

very likely to infer from a certain pattern of joints, which he has associated in his mind with the term "compression joints," that the rock mass has necessarily been simply compressed, and, moreover, frequently assigns a definite direction to the supposed pressure. A system of nomenclature involving no reference to stresses would seem much better, and the writer suggests the two simple terms, "slip" and "rip" joints. Such terminology would at least avoid incumbering the description of fairly simple facts with names which permit the possibility of unintended implications in the reader's mind.

RELATIONS BETWEEN ROCK DEFORMATION AND CAUSAL FORCES

This subject, sometimes discussed under the heading of "Stress and Strain," is also complicated by the variable usage of stress terms. But, in addition, there are several other sources of difficulty, which will be set forth below.

In considering the deformational record itself, it must first be noted that the absolute strain is rarely determinable. For example, if pebbles assumed to have been at one time approximately spherical are found distinctly ellipsoidal and oriented in a regular fashion, the absolute amounts of the three principal strains giving the observed deformation cannot be found from the record alone. That is, whether a certain pebble has been elongated in one direction and shortened in two directions at right angles to this, or has been shortened unequally along the three principal axes, is not clear from the mere evidence at hand. However, by making the plausible assumption that its volume has remained nearly constant, it is possible to derive the approximate unit strains. It may be noted in passing that the generalization that planes of no distortion are planes of maximum shear is founded on this underlying assumption and the application of the strain theory, both of which are reasonably used in connection with large strains. Suppose, however, as a second example, that the deformation was indicated only by a pattern of slip joints. These might be interpreted in terms of a maximum shortening in one direction and elongation in another, but the amounts of these unit strains could be estimated only very roughly. A procedure such as drawing a circle and an ellipse of equal areas so that the lines joining their intersections show the same angular relationship as the observed

slip joints would assume that one version of the strain theory evaluates the conditions of failure exactly, which is clearly unjustifiable as a general method. Usually, then, the strain inferred from a deformational structure can be expressed only qualitatively by giving the directions of greatest elongation and shortening. Furthermore, since a state of even approximate elasticity cannot be assumed for rocks under all conditions of deformation, no proportional relation of stress to strain can be used, so that, for the object of determining stress, a qualitative statement of strain is all that is warranted.

The internal stress condition at the time of deformation may be inferred directly from the record, or from the strain, the second method being the commonest, because many structures diagram the strain for the observer. Now, in absolute terms, the stress condition is even less determinable than the strain. The situation given above may be analyzed from a slightly different viewpoint by noting that both the stress and the strain theories are primarily based on the difference between the principal stresses and strains, and evaluate the absolute intensities only as modifying factors. In dealing with strain, this difference, which is inferred from the structural record, is used, together with the assumption that the volume change has been negligible, to determine qualitatively the absolute unit strains; that is, these are regarded as consisting of both shortening and elongation. But no similar assumption guides the determination of the internal stress condition absolutely, and, because of the possibility of plastic deformation, elongation does not necessarily mean internal tension. In fact, there are general grounds for believing that the internal stress condition at any random point in the earth's crust is predominantly compressional. In special cases, of course, such structures as rip joints may indicate internal tension. The general statement of the internal stress condition from the strain is therefore not given absolutely, but is indicated in terms of the greatest and least stress axes, the second of which may or may not represent tension.

Bearing in mind the underlying assumptions indicated above, which should be tested for any specific case, we may summarize briefly the relations between internal stress and strain by saying that the direction of greatest elongation corresponds with the least

stress axis, and that of greatest shortening with the greatest stress axis.

The relations of causal stress, however, are not amenable to any generalization. The complications that arise are illustrated in a simple way by Figures 4 and 5. It is clear that an observer who had interpreted the strain and internal stress for the portion *ABCD* (or for the whole of the areas shown) would not be able to judge whether the causal stress was a simple shear or a combination of simple tension and compression, unless he had some other independent evidence to guide him. The presence of this independent evidence is essential, and, whether expressed or not, is as necessary to any inference of the causal stress as the strain record. This fact is not uncommonly lost sight of, because accepted interpretations do not always show clearly the fundamental way in which certain evidence is used as a basis for the conclusions reached. The following familiar example is treated in such a way as to show that two independent lines of evidence enter the consideration, and the reader may note that one of these is sometimes expressed only by an adjective, or just taken for granted, a procedure which may lead students to make faulty interpretations from other cases where all the emphasized evidence is present, but that implied is not. The example is that of fracture cleavage in an incompetent bed, a record which may be used to indicate a certain strain. The additional independent evidence is supplied by the fact that the beds have been folded, which suggests that there has been shear between the strata. If the attitude of the beds was caused by block faulting, the ordinarily assumed limitation in the kind of the causal stress would not be justifiable. Furthermore, if any other conditions are indicated which would complicate the situation, the case becomes indeterminate in terms of the usual rules. Among such conditions might be mentioned the presence of a series of more or less incompetent beds, which permit the shear developed by folding to be resolved into a variety of causal stresses on the different units. But to return to the simple case, where, ideally, we have fracture cleavage in a small incompetent bed between two large competent beds that have been folded, the strain interpreted from the joint pattern is assumed to be the result of a

shear between the beds combined with normal gravitatic pressures. Accordingly, a certain conclusion is obtained as to the direction of the movement between the beds, and a more or less definite causal stress for the fracture cleavage is indicated, namely, rotational compression which acted along one of a fairly well-limited range of directions.

The example given contains the implication that causal stress is defined as the external stress acting on the incompetent bed considered, or, in general, on the more or less homogeneous mass of rock under observation. Such usage is probably the commonest, but by no means the only one. A causal force which it might be desirable to determine would be that which folded the strata. The nature of the deformation of the larger unit formed by the folded beds could be inferred, or determined by other data, in which case these would form confirmatory, not independent evidence. The cause of the deformation of this larger unit might have been one of several possibilities, such as the simple compression of the beds, or the drift of one portion past the other. Clearly some new independent evidence would be necessary to fix the nature of this causal force. In short, there is a general separation of causal forces into what may be called "generations," each set giving rise to certain forces and itself the product of others. Usually the investigation proceeds from the consideration of small units to that of increasingly larger ones, and each step requires additional independent evidence. It is clear that the heterogeneity of rocks when taken in large masses is such that the relations between the forces of different generations may be very complex.

The determination of the causal force is thus a problem to be left largely to the investigation of special cases. Valuable inferences may be made under certain conditions, as, for example, those from cleavage in folded rocks, but the person applying these conclusions elsewhere must keep in mind the assumptions involved and be certain that they are equally true for the case he is investigating. Although this paper deals primarily with the smaller units of structure, the same precautions apply to the consideration of deformation and earth forces on a large scale. For example, the folded mountain ranges show the strain, but the determination of the forces causing

this deformation involves other assumptions, such as the predominance of an all-pervasive tangential pressure in the earth's crust, the modification of this by relative vertical movements of the major segments, or by subcrustal flow, and so on.

In closing it may be noted that some of the confusion due to the variable usage of stress terms may be avoided by employing stress terms only in connection with causal stresses, that is, only with the meaning that the geologist is most apt to assign to them anyway. Professor Leith, in his textbook on *Structural Geology*, has already given considerable impetus to this usage by relating structural features to strain, and emphasizing the lack of a definite relationship between the structures and the causal stresses.

COAST RANGE INTRUSIVES OF SOUTHEASTERN ALASKA[1]

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ABSTRACT

Data are presented to show that the Coast Range intrusives of southeastern Alaska may be tentatively grouped in a number of belts wherein one general type of igneous intrusive rock predominates.

Intrusive stocks and batholiths in a wide belt of folded sediments and volcanics to the southwest of the Coast Range batholith have an average composition of a quartz-ose diorite; the Coast Range batholith, throughout a considerable length, consists predominantly of quartz diorite in the southwest portion, granodiorite in the core, and quartz monzonite in the northeast portion. Small stocks of gabbro and ultrabasic rocks also occur in the Alexander Archipelago to the southwest of the main Coast Range batholith. Each of the major types of plutonic rock occurring in large volume is accompanied by a small volume of a highly sodic leucocratic facies and by aplite dikes whose composition probably varies with the composition of the rock with which they are genetically associated, and in whose origin mineralizers have played an important part.

The Coast Range intrusives and those of the Sierra Nevada are compared, and it is shown that both have a similar variation in composition and mode of geographic distribution, which is probably due to the same structural cause.

INTRODUCTION

During the five field seasons from 1921 to 1925 inclusive, the writer has been engaged in the investigation of mineral deposits and in reconnaissance mapping of the geology of southeastern Alaska. Incidental to this work, particular attention has been paid to the Coast Range intrusives and a considerable amount of new data obtained. As a result of this work and of a study of the literature, a number of generalizations have been reached which are summarily stated here. A more thorough treatment of the subject will appear in a publication of the U.S. Geological Survey. The writer must, however, emphasize the fact that we have available only a most superficial reconnaissance of the Coast Range intrusives in Alaska and British Columbia. Any general conclusions which may be drawn must, therefore, be considered as highly tentative and of the nature of a first approximation only.

[1] Published by permission of the Director, U.S. Geological Survey.

The most important papers containing data bearing on this subject are by A. C. Spencer,[1] F. E. and C. W. Wright,[2] C. W. Wright,[3] Adolph Knopf,[4] R. M. Overbeck,[5] L. G. Westgate,[6] Theodore Chapin,[7] and A. F. Buddington.[8]

The writer is indebted to F. E. and C. W. Wright for the opportunity to examine a large number of thin sections of rocks collected by them throughout southeastern Alaska. He is also under obligations to his assistant, W. B. Jewell, who in 1925 made a reconnaissance across the batholith by way of the Chickamin River, and prepared a report on this section.

Johannsen's system of rock classification is used,[9] with some modifications which are noted here. An upper limiting ratio of 10 per cent potassic feldspar to total feldspar, instead of 5 per cent, is chosen to delimit quartz diorite from granodiorite in order better to express the field relations. Only rocks with a ratio of 10 per cent or more of potassic feldspar to total feldspar are included in the monzodiorites. The plagioclases, albite, oligoclase, andesine, and labradorite are delimited in their upper range by a ratio of 10, 30, 50, and 70 per cent, respectively, of the anorthite molecule. Many of the rocks grouped here as quartz diorite would be classed as granodiorite

[1] A. C. Spencer, "The Juneau Gold Belt, Alaska," *U.S. Geol. Survey Bull. 287*, 1906.

[2] F. E. and C. W. Wright, "The Ketchikan and Wrangell Mining Districts, Alaska," *U.S. Geol. Survey Bull. 347*, 1908; "A Geologic Reconnaissance of Glacier and Lituya Bay Regions," U.S. Geol. Survey, unpublished manuscript.

[3] C. W. Wright, "Geology and Ore Deposits of Copper Mountain and Kasaan Peninsula, Alaska," *U.S. Geol. Survey Prof. Paper 87*, 1917 (contains sections on petrography by H. E. Merwin).

[4] Adolph Knopf, "The Sitka Mining District," *U.S. Geol. Survey Bull. 504*, 1912; "Geology of the Berners Bay Region, Alaska," *U.S. Geol. Survey Bull. 446*, 1911; "The Eagle River Region," *U.S. Geol. Survey Bull. 502*, 1912.

[5] R. M. Overbeck, "Geology and Mineral Resources of the West Coast of Chichagof Island," *U.S. Geol. Survey Bull. 692-B* (1919), pp. 91–136.

[6] L. G. Westgate, "The Geology and Mineral Resources of the Area East of Behm Canal," U.S. Geol. Survey, unpublished manuscript.

[7] Theodore Chapin, "Geology and Mineral Deposits of the Ketchikan District," U.S. Geol. Survey, unpublished manuscript.

[8] A. F. Buddington, "Coincident Variations of Types of Mineralization and of Coast Range Intrusives," *Econ. Geol.*, Vol. XXII (1927), pp. 158–79.

[9] Albert Johannsen, "A Quantitative Mineralogical Classification of Igneous Rocks —Revised," *Jour. Geology*, Vol. XXVIII, Nos. 1–3 (1920), pp. 38–60, 158–77, 210–32.

if considerable of the potassium present in the mineral biotite occurred in potassic feldspar instead.

The Coast Range intrusives are the dominant geologic feature of southeastern Alaska. They constitute a portion of a great com-

FIG. 1.—Generalized sketch of Coast Range intrusives in southeastern Alaska

posite batholith and its attendant satellitic intrusives which extend for over 1,100 miles northwestward into Yukon Territory from the Fraser River in British Columbia. On the mainland, from Vancouver to Skagway, the Coast Range batholith forms the backbone of the Coast Range and is exposed either directly along the shoreline or not far inland. Dikes, stocks, and batholiths are found locally on

Vancouver Island and the Queen Charlotte Islands, and abundantly throughout most of the Alexander Archipelago, which are believed to belong to the same general period of intrusion as the Coast Range batholith and to be genetically allied to it. The mainland batholith reaches a maximum width of 110 miles, and is much wider south of the Skeena River in British Columbia than north of it. In southeastern Alaska and that portion of the territory of British Columbia which adjoins it on the east, the Coast Range batholith varies from 35 to 60 miles in width, and averages about 50 miles wide for a length of about 350 miles.

The term "Coast Range batholith" is here applied to the main large batholith of the mainland, and the term "Coast Range intrusives" is used to include both the great batholith and the outlying intrusives of the mainland and the Alexander Archipelago believed to be genetically allied to it.

The Coast Range intrusives may be naturally grouped into six approximately parallel belts (Fig. 1) based upon the mode of occurrence, the environmental surroundings, and the character and range in variation of composition.

EASTERN BORDER BELT

The border belt east of the main batholith is for the most part relatively inaccessible and lies almost wholly within British Columbia. There is very little exact information as to the character of the intrusives.

The outstanding feature of the country rocks in this belt is the absence of any widespread igneous metamorphism and the relatively meager local contact metamorphic effects produced by the Coast Range batholith. The country rocks are closely folded and comprise slates, tuffaceous graywacke, and andesitic volcanics locally altered to greenstone. Limestone is present in certain areas. There are no phyllites or crystalline schists except for a very local development immediately adjacent to the Coast Range batholith.

The number of intrusive stocks and batholiths varies markedly within this eastern border belt. Hanson[1] states that between the

[1] George Hanson, "Reconnaissance between Skeena River and Stewart, B.C.," *Geol. Survey of Canada, Sum. Rept.* (1923), p. 37a.

Skeena and Nass rivers in British Columbia, the eastern border of the batholith is irregular and there are a number of apophyses and outlying stocks of granodiorite, but that between the Nass River and Portland Canal it is approximately straight.

In the Hyder district at the head of Portland Canal there is a large mass of granitoid rock which is intrusive into the Hazelton group of beds of Jurassic age. The mass is older than the main Coast Range batholith in this vicinity, and has been locally very intensively mechanically mashed and altered by the thrust exerted by the younger magma. This batholith, named the Texas batholith, consists of a core of granodiorite, near quartz monzonite in composition, with chilled marginal facies of quartz diorite. The average composition of the main body is 48 per cent andesine, 20 per cent potassic feldspar, 19 per cent quartz, and the remainder hornblende, biotite, and accessories.

Small masses of gabbro and gabbro-diorite are also found. These are older than the main Coast Range batholithic intrusives, but their relation to the Texas batholithic rocks is not known.

The composition of the outlying masses in this belt, genetically associated with the Coast Range batholith, in part varies markedly in accordance with the size. Certain large stocks are granodiorite, varying toward quartz monzonite, whereas dikes may vary from granodiorite to quartz diorite and diorite.

COAST RANGE BATHOLITH

Of seventy-eight specimens taken at intervals across the Coast Range batholith along the west side of Portland Canal and along the Chickamin and Stikine rivers, there were twenty-eight granodiorites, twenty-six quartz monzonites, sixteen quartz diorites, two granites, two hornblende-biotite diorites, two monzonites, and one each of hornblendite and gabbro. This probably gives an approximate idea of the relative quantitative distribution of the various types of igneous rocks within this portion of the mainland batholith.

The composition of the batholith as a whole, as indicated by specimens taken at intervals along three different cross-sections a total of 150 miles apart, is given in Table I, No. 1. The accessory minerals consist largely of titanite and magnetite, with a little asso-

ciated apatite and a trace of zircon. This average, however, must not be taken as indicating that the bulk of this portion of the batholith is granodiorite. On the contrary, quartz monzonite is of equal bulk with granodiorite, and quartz diorite somewhat less so.

TABLE I

APPROXIMATE MINERAL COMPOSITION OF COAST RANGE INTRUSIVES IN SOUTHEASTERN ALASKA, GROUPED BY BELTS

	Oligoclase	Andesine	Potassic Feldspars	Hornblende	Biotite	Quartz	Accessories	Pyroxene
1. Average of 60 specimens taken at intervals across three different sections of Coast Range batholith	....	*44	21	5	6	22	2	....
2. Average of 65 typical specimens from Prince of Wales-Chichagof belt	....	58	5	20.5	3.5	9.5	2.5	1
3. Average of 20 typical specimens from Wrangell-Revillagigedo belt	....	53	6.5	8	11	19	2	....
4. Average of 20 typical specimens from western portion of Coast Range batholith	....	54	2	11	11	20	2	....
5. Average of 44 typical specimens from core of Coast Range batholith between Portland Canal and Stikine River	....	44	21	6	7	20	2	....
6. Average of 16 typical specimens from eastern portion of Coast Range batholith between Portland Canal and Chickamin River	....	*37.3	32.7	0.1	4	24.5	1.5	....
7. Average of 5 specimens of oligoclase quartz monzonite from eastern portion of Coast Range batholith on the Stikine River	31	.....	37	0	1.5	30	0.5	....
8. Average of 21 specimens from Dall-Baranof belt	....	62	5.5	6.5	3.5	20	2	0.5
9. Average of 4 oligoclase granodiorite aplites from Wrangell-Revillagigedo belt	56	.....	14	....	....	30	....	....
10. Average of 3 quartz monzonite aplites from core of Coast Range batholith	30	....	32	....	....	36	2	....
11. Average of 2 granite aplites from eastern portion of Coast Range batholith	15	.....	48	....	....	37	....	....

* Oligoclase-andesine.

The western part of the batholith throughout southeastern Alaska is a quartz diorite for a width of 5–15 miles from the contact. The average composition of twenty specimens from this belt is given in Table I, No. 4.

The core of the batholith, between the Stikine River and Portland Canal, consists predominantly of granodiorite with some asso-

ciated quartz monzonite and quartz diorite and occasional small masses of diorite and more basic types. The average of forty-four specimens from the core of this portion of the batholith is that of a granodiorite and is given in Table I, No. 5.

The eastern flank of the batholith is practically unknown from a quantitative petrographic standpoint. For a width of about 12 miles and a length of about 25 miles between the Portland Canal and the Chickamin River it is a quartz monzonite. The average of sixteen specimens from this belt is given in Table I, No. 6. On the Stikine River the rock of the eastern border belt is a siliceous oligoclase quartz monzonite. An average of five specimens from this belt along this river is given in Table I, No. 7.

There is a variation in composition both lengthwise of the batholith and across it, but in this area the lengthwise change is very much less marked than the crosswise variation.

The variation across the batholith along the Stikine and Chickamin rivers and along Portland Canal may be summarized as in general from a hornblende-biotite andesine quartz diorite on the southwest to a biotite oligoclase or oligoclase-andesine quartz monzonite on the northeast, with rock averaging that of a granodiorite in the core. This gradation is not continuous, however, but is irregular, with abrupt alternating bands. Along Portland Canal, in the core of the batholith, there are at least two broad belts of quartz monzonite interbanded with correspondingly broad belts of granodiorite, which in turn is interbanded with quartz diorite. On the Stikine and Chickamin rivers no quartz monzonites were noted in the core of the batholith, but quartz diorite bands are found, and on the Stikine River there are locally small masses of diorite and more basic rocks. There is a tendency for the rocks to contain more potash feldspar, a more sodic plagioclase, and less ferromagnesian minerals in passing from the southwestern to the northeastern border of the batholith. Hornblende is wholly absent from the quartz monzonite of the eastern portion, only a little biotite is present, and the percentage of quartz is much higher than in the rocks to the southwest. Wherever reaction and injection gneisses are present within the batholith, the rocks are often very variable in composition within short distances. Inclusions of country rock, varying from large belts to

disintegrated shreds, are found within the batholith. These are usually restricted to certain belts, where all gradations may be found from schist through injection and reaction gneisses to normal intrusive.

A diagrammatic representation of the writer's conception of the relations of the various types of Coast Range intrusives is shown in Figure 2. The relations shown differ slightly from those described by Dolmage and figured by Schofield for that portion of the batholith to the southeast of the area considered here. Dolmage,[1] in describing about 150 miles of the Coast Range batholith to the

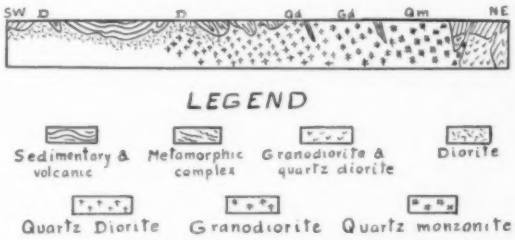

FIG. 2.—Generalized structure section across Coast Range intrusives of southeastern Alaska.

south of Portland Canal, writes: "These more acid types [granodiorite and quartz monzonite] show a tendency to lie towards the central part of the batholith, but there are exceptions to this." Schofield[2] gives a diagrammatic section of the Coast Range batholith, based on Dolmage's data, in which he shows a narrow zone of quartz diorite on the northeastern side of the batholith and a wider belt on the southwestern side, with grandiorite forming the core. For that portion of the batholith which he has studied, the writer would emphasize a pronounced variation in the distribution of the rock types within the batholith, whereby the more alkalic and siliceous types tend to lie toward the northeast. The question may also

[1] Victor Dolmage, "Coast and Islands of British Columbia between Douglas Channel and the Alaskan Boundary," *Geol. Survey of Canada, Sum. Rept.* (1922), p. 16A.

[2] S. J. Schofield, "The Britannia Mines, British Columbia," *Econ. Geol.*, Vol. XXI (1926), p. 277.

be raised as to whether the quartz diorite mapped by Dolmage on the northeast border of the batholith instead of being a chilled, border facies, is rather an older intrusive.

WRANGELL-REVILLAGIGEDO BELT

Within this belt about half the siliceous intrusive rocks are hornblende-biotite-andesine quartz diorites with only a trace to 2 per cent of potassic feldspar; and half are relatively low potassic hornblende-biotite-andesine granodiorites, with usually from 7 to 12 per cent potassic feldspar. The average composition of twenty specimens from this belt is given in Table I, No. 3. The differences between these outlying intrusives and the quartz diorite of the western border of the batholith are slight. The percentage of andesine, biotite, and quartz is practically the same; the potassic feldspar is considerably higher in the intrusives of the Wrangell-Revillagigedo belt, and the percentage of hornblende somewhat lower.

PRINCE OF WALES–CHICHAGOF BELT

To the west of the Wrangell-Revillagigedo belt, and paralleling it, is another in which intrusive masses, but of different character, are common, and the country rock consists predominantly of slates, limestone, graywacke, greenstone, and dynamically metamorphosed schistose rocks, with some local crystalline schist and marble. The stage of metamorphism in general is much less advanced than in the belt to the east, though locally adjacent to large igneous bodies it may be intense.

This belt is 40 miles wide at the north, but may not be much over 5 miles wide on Kupreanof Island; it widens on Etolin Island, and is about 25 miles in width from there south.

The igneous masses predominantly consist of hornblende-andesine diorites and monzodiorites and quartzose variants of these. Hornblende diorites predominate. A few large masses of younger intrusive granites are present in the southern portion. Granodiorites and quartz diorites are present as variants of the predominant less quartzose masses, and occasionally as separate stocks. A few masses of the various ultrabasic rocks are present. Locally the diorites grade into hornblendites and gabbros as marginal variants.

Throughout this belt there are local marginal variants of the

albite or albite-oligoclase type of diorite, monzodiorite, granodiorite, and quartz diorite, as well as dikes of albite and albite-oligoclase trachyte.

Thus, though certain types of intermediate igneous rocks predominate in this belt, extreme differentiates, such as gabbro and gabbroic hornblendites on the one hand and albite varieties of diorite, monzodiorite, and quartz diorite on the other, are common.

The intrusive rocks of this belt thus differ from those in the belt to the east, in general, in that the predominant rock belongs to the diorite family as contrasted with a quartz diorite.

The average composition of sixty-five specimens (35 diorites, 6 monzodiorites, 6 quartzose monzodiorites, 6 quartzose diorites, 6 quartz diorites, 4 granodiorites, and 2 gabbro diorites) is given in Table I, No. 2. Younger intrusive granites which are present in this belt are not included in this average. The average composition is that of a quartzose hornblende diorite with considerable potassic feldspar. As contrasted with the average composition of the belt to the east, it shows a very decided decrease in quartz and biotite, and a very marked increase in the amount of hornblende. The total content of ferromagnesian minerals is considerably higher, and magnetite and pyroxene are the predominant accessory minerals. As in the case of the Wrangell-Revillagigedo belt, there is in a general way a local regional variation in the percentage of potassic feldspars present in the rocks.

KUIU-HECETA BELT

The Kuiu-Heceta belt may be considered an elliptical-shaped area within the Prince of Wales–Chichagof belt on the east and the Dall-Baranof belt on the west, in which intrusives are relatively sparse and the degree of metamorphism is correspondingly slight. The stage of metamorphism of the pre-Tertiary rocks in this belt is less than in any other area in southeastern Alaska. Many of the oldest beds (Ordovician and Silurian) are richly fossiliferous, with comparatively well-preserved fossils.

DALL-BARANOF BELT

Within the Dall-Baranof belt intrusive stocks and batholiths are more common than in the adjoining Kuiu-Haceta belt on the

east, and the composition of the more common intrusives appears to differ from that of the prevailing types in the Prince of Wales–Chichagof belt. But here again our knowledge of the composition and relations of the intrusives is scanty, and any inferences drawn need further substantiation.

The average composition of twenty-one specimens (13 quartz diorites, 4 granodiorites, 3 diorites, and 1 gabbro-diorite), exclusive of ultrabasic types, collected at various points within the belt, is given in Table I, No. 8. The rocks, on the average, are much more siliceous and carry less ferromagnesian minerals than the average of the Prince of Wales–Chichagof belt, and are slightly more feldspathic and carry less ferromagnesian minerals than the average of the Wrangell-Revillagigedo belt.

On Baranof Island, highly mashed hornblende diorite and hornblende gabbro occur on Bear Lake and Silver Bay; serpentine, on the north side of Red Bluff Bay; and amphibolite, with associated nickeliferous pyrrhotite, on Snipe Bay. Augite diorite and gabbro occur near Squaw Mountain on Dall Island.

There is a wide variation in the types of intrusives, but quartz diorites, and to a lesser extent granodiorites, are predominant. The quartz diorites vary from leucocratic types with less than 5 per cent ferromagnesian minerals (mostly biotite), 60–65 per cent plagioclase (oligoclase or oligoclase-andesine), and 30–35 per cent quartz, to quartzose hornblende-andesine diorites. Leucocratic oligoclase grandiorites also occur.

On Dall and Suemez islands, moderately to coarsely crystalline schists are restricted to the immediate vicinity of the intrusive masses.

But few data are available on the rocks of Baranof Island. Of seven specimens from the larger masses, all except one were quartz diorites; the exception is an oligoclase granodiorite of leucocratic character. The rocks are peculiar in their low (8.5) percentage of ferromagnesian minerals.

ROCK TYPES

The ultrabasic and gabbroic rocks in southeastern Alaska are relatively sparse when compared with the great volume of more siliceous and alkalic siliceous intrusives. But they are, nevertheless,

widely distributed throughout the Alexander Archipelago and near the western border of the mainland batholith. Taken in the aggregate, they form a very considerable volume of intrusives, and there is no doubt but that there are a great many masses which have not yet been found. The ultrabasic group includes such types as dunites, pyroxenites, hornblendites, peridotites, troctolites, saxonites, wehrlites, and probably many others.

Diopside pyroxenites are associated with the olivine-rich rocks, whereas diallagites are associated with hornblendites and gabbros, and bronzitites with norite. So far as studied in this region, magnetite with a little associated ilmenite occurs in marked magmatic concentrations and segregations exclusively with the diallagite and hornblende-augite rocks, the latter usually associated with hornblendites. Apatite tends to be markedly concentrated in many of the hornblendites and hornblende-augite rocks; and pyrrhotite, with a little associated pentlandite and chalcopyrite, accompanies certain of the norite bodies, amphibolite, bronzitite, and troctolite.

The most marked and characteristic feature of the hornblendite masses is their wide and abrupt variation in texture, and the local abundance of pegmatitic facies, which may vary widely in composition. Locally, hornblendite masses have developed as marginal facies to monzodiorite, quartz diorite, granodiorite, and diorite.

The gabbroic rocks include norites, augite gabbro, augite-biotite gabbro, and hornblende gabbro. The gabbros are relatively sparse. They occur in association with ultrabasic masses and also as small isolated stocks.

Gabbro-diorite is more common than true gabbro, though it, too, occurs in only small volume. It forms local basic border facies to the dioritic intrusives in the Alexander Archipelago, and also occurs as small separate stocks. The plagioclase is usually near Ab_1An_1, an andesine-labradorite. Hornblende is commonly the predominant ferromagnesian mineral and forms from 35 to 65 per cent of the rock. Pyroxene may be present as an accessory mineral, and in some cases may be the predominant ferromagnesian mineral. Quartz and orthoclase may be present as accessory minerals. Magnetite is always present, and in certain cases shows a marked con-

centration up to 10 per cent or more. Biotite may be present, but is usually restricted to the more siliceous rocks.

TABLE II

MINERAL COMPOSITION OF COAST RANGE INTRUSIVE TYPES

	Albite or Oligoclase	Andesine	Hornblende	Biotite	Potassic Feldspars	Quartz	Accessories
1. Average composition of 28 diorites in Prince of Wales–Chichagof belt	....	62.5	27	2.5	1.5	4	2.5
2. Average composition of 7 monzodiorites in Prince of Wales–Chichagof belt	....	56	17	2	19	4	2
3. Albite Monzodiorite, Mamie Mine, Prince of Wales Island	71	....	5	....	23	....	1
4. Average composition of 11 quartzose diorites from Prince of Wales–Chichagof belt	....	63	23	1	1	10	2
5. Average composition of 20 quartz diorites, west border of Coast Range batholith	....	53	11	12	2	20	2
6. Average composition of 20 quartz diorites from Wrangell-Revillagigedo belt	....	54	8	11	6.5	19	2
7. Average composition of 7 quartz diorites from Baranof Island	....	62	3.5	5	5	23.5	1
8. Average composition of 9 albite or oligoclase quartz diorites from Alexander Archipelago	71	....	0.7	2	1.8	24.5	....
9. Average composition of 10 granodiorites from Wrangell-Revillagigedo belt	....	50	7.0	13	10.0	18	2
10. Average composition of 15 granodiorites from core of Coast Range batholith	....	46	8.5	7.5	15	21.5	2
11. Average composition of 9 granodiorites from Alexander Archipelago west of Wrangell-Revillagigedo belt	....	56	7	5	12	19	1
12. Average composition of 5 specimens from a marginal apophysis or stock on the east side of Coast Range batholith	....	48	4	6	17	19.5	2.5
13. Average composition of 3 oligoclase granodiorites from Alexander Archipelago	52	....	1	1.5	12	33	0.5
14. Average composition of 9 quartz monzonites from core of Coast Range batholith	....	37	6.5	4	30.5	20	2
15. Average composition of 16 quartz monzonites from eastern portion of Coast Range batholith	....	37.3	0.1	4	32.7	24.5	1.35
16. Average composition of 5 oligoclase quartz monzonites from eastern portion of Coast Range batholith on Stikine River	31	....	....	1.5	37	30	0.5
17. Average composition of 3 granites from Alexander Archipelago	13	....	1	2	61	23	....

The average composition of the predominant types of Coast Range intrusives is given in Table II. They are for the most part normal in their composition, and only a few points regarding them need to be noted.

A study of the mineral relations between the diorites and quartz diorites shows that up to a certain limit an increase of quartz in the diorites, though it may be accompanied by a decrease in the amount of hornblende, is not normally accompanied by a change of hornblende to biotite; but that, on the other hand, in the change from quartzose diorites to quartz diorites, there is normally a corresponding alteration of the hornblende to biotite. Within the quartz diorites the amount of hornblende or of hornblende and biotite may vary very markedly, though the percentage of quartz remain constant.

In the quartz diorites of the Coast Range batholith, hornblende and biotite combined vary from 6 to 35 per cent. Usually where the combined amount is between 19 and 27 per cent, hornblende predominates slightly over biotite; if the combined percentage of both constituents is 18 per cent or less, biotite usually predominates over hornblende; but there are exceptions to both generalizations. In the granodiorites of the core of the Coast Range batholith, hornblende and biotite combined vary from 8 to 25 per cent. Where the combined percentage of the ferromagnesian minerals is greater than 13 per cent, hornblende usually exceeds biotite, and where the combined percentage is 12 per cent or less, biotite exceeds hornblende, but exceptions are common. The quartz monzonite of the central portion of the core of the Coast Range batholith is in general highest (10.52 per cent) in hornblende and biotite, and hornblende is greater in amount than biotite. In the quartz monzonite of the eastern portion of the core on Portland Canal, the total amount (8 per cent) of ferro-magnesian minerals is smaller, and biotite (5 per cent) exceeds hornblende (3 per cent). Along the eastern portion of the batholith, the total amount of ferromagnesian minerals is still less (4 per cent), and hornblende is practically absent.

In the central part of the Coast Range batholith, at a distance from included slabs or blocks of schist, pegmatites and aplites are rare; but along the western border, in the Ketchikan, Wrangell, and the southern part of the Juneau districts, they are abundant; and the adjacent schists as far north as Juneau are unusually intimately penetrated by them parallel to the schistosity in lit-par-lit fashion, so as to constitute injection gneisses over belts several

miles or more in width. Where pegmatites and aplites together are not abundantly developed, aplites are usually much more common, and they may be found as dikes far away from the nearest igneous intrusive and widely distributed. The average composition of several types of aplite is given in Table I, Nos. 9, 10, and 11.

Lamprophyre dikes are locally very abundant within the Coast Range batholith, and are sparsely distributed throughout the Alexander Archipelago. The predominant type of lamprophyre within the Coast Range batholith is of a type allied to both spessartite and camptonite. Plagioclase (oligoclase or andesine variety) appears to be more predominant in most of the lamprophyres of this area than is typical for them elsewhere, and the rocks grade toward malchite. Brown hornblende forms from 10 to 50 per cent of the rock, and potassic feldspars are only occasionally present. Secondary minerals are always present and may be very prominent. They comprise calcite, chlorite, and epidote. Other types of lamprophyres found are kersantite, minette, and garganite.

STRUCTURE

In the mainland batholith the rocks are prevailingly gneissoid with a steep dip throughout to the northeast. Local zones, in places of great width and length, have been noted in which the minerals have been crushed after complete consolidation of the magma, but the gneissic structure is of the primary type formed during and before the completion of the processes of consolidation. The two most important factors in giving rise to the gneissoid character, where evidences of shearing and mashing are absent or practically so, as is usually the case, are (1) the parallel dimensional orientation of the inequidimensional mineral grains, and (2) the relative segregation of the light and dark minerals, in an indistinct fashion, into *en échelon* lenses, or in small patches. Most of the abundant biotite crystals are chunky in form, and many of them are oriented with the *c* axis parallel to the foliation, both of which features are contrary to the usual form and orientation in secondary recrystallized gneisses. Not a trace of crushing or granulation was found in twenty specimens examined of quartz diorite between Portland Canal and

Taku Inlet. The writer could find no relation between the zones of crushing and the type of rock or the border of the batholith.

The structure of the stocks and batholiths of the Alexander Archipelago is variable, dependent upon several factors. The margins of the bodies often locally show a gneissic structure. The granodiorites and quartz diorites are usually gneissoid, whereas the diorites and gabbros are more often massive. The outlying intrusive masses, like the mainland batholith, also exhibit local shear zones in which the minerals are mashed and crushed.

The lamprophyre dikes which are locally so abundant in the Coast Range batholith predominantly strike across the general NW. grain of the batholith with trends between N. 10° E. and N. 45° E., although to a minor extent they are approximately parallel to the gneissic structure or to the bedding of the sediments.

A structure section portraying the writer's idea of the relations of the various intrusives to their mode of occurrence is given in Figure 2.

INTERRELATIONS OF THE ROCK FACIES

The ultrabasic group of rocks of the Alexander Archipelago are older, and are intruded by the group of more siliceous-alkalic types, which so greatly exceed them in volume.

Granodiorite in stocks and small batholiths may show marginal variants to quartz diorite, gabbro-diorite, diorite, monzodiorite, and very rarely to syenite. A decrease in potassic feldspar and quartz locally on the margins is a common feature. On the eastern border of the Coast Range batholith, quartz monzonite locally shows border apophyses or stocks of granodiorite, and outlying dikes as basic as quartzose diorite. The writer has not seen any actual intrusive phenomena between such types as diorite, quartz diorite, granodiorite, and quartz monzonite. But the abrupt change from one type to another within the Coast Range batholith and general considerations suggest that there must have been successive movements of magma of changing composition extended over a long period of time.

Granite (potassic) is the youngest of the major members of the plutonic complex, and is found uniformly to bear intrusive relations

toward each of the other types. Geographically it has been found, not, as might be expected, on the eastern border of the Coast Range batholith, but as small stocks and batholiths in the Alexander Archipelago.

Accompanying each of the rock types with andesine plagioclase (such as diorite, monzodiorite, quartz diorite, and granodiorite) in the Alexander Archipelago there is a relatively very small volume of more sodic (albite or oligoclase) leucocratic variants, such as albite or oligoclase diorite, albite or oligoclase quartz diorite, etc. A typical analysis and average analyses of such types are given in Table II, Nos. 3, 8, and 13. Such types are also characterized by a very low content of ferromagnesian or accessory minerals. They usually occur in small volume as marginal variants, or perhaps more commonly as satellitic dikes, sheets, apophyses, and small stocks.

A pegmatitic facies may be associated with each of the major rock types except dunite and peridotite. The plagioclase of the pegmatite is usually more sodic than the rock with which it is associated.

Aplite dikes are associated with each of the rock types from diorite to granite. The writer would suggest it as a possibility that in this region a particular type of aplite is associated in general with a particular type of plutonic in such a fashion that the aplite contains a more sodic plagioclase and a higher percentage of potassic feldspar and quartz than the magma with which it is genetically associated. Average analyses of three types of aplite from different belts are given in Table I, Nos. 9, 10, and 11. This suggestion, however, is based on few data, and further work is necessary either to substantiate it or to render it untenable.

Lamprophyre dikes are the youngest members of the intrusive series.

ORIGIN OF VARIATIONS

Only a few points will be discussed here in connection with the great problem of the origin of the various types of the Coast Range intrusives.

The hornblendites of this region appear to have originated from the consolidation of a gabbroic magma which contained an unusually high percentage of mineralizers. The most pronounced feature of

the hornblendite masses is their wide and abrupt variation in texture and the local abundance of pegmatitic facies which may vary widely in composition. Bands of the hornblendite are often composed of crystals averaging 6 inches long and 3 inches broad. The most common mineral of the pegmatite facies, in addition to hornblende, is albite; biotite is locally common, and titanite and apatite are often abundant. Albite also occurs in separate veinlets. Locally ilmenitic magnetite veins are present. In thin section, many of the hornblendite masses are found to be unusually rich in apatite, containing up to 4 per cent. All of these features suggest the importance of mineralizers in the magma. Some, at least, of the hornblendites, and especially the feldspathic types, are of such a composition that if calculated in terms of anhydrous minerals they may be shown to be equivalent to an olivine gabbro. For example, a chemical analysis of a hornblendite from Port Snettisham, recalculated in terms of normative minerals, gives andesine-labradorite, 54.3 per cent; orthoclase, 1.7 per cent; ilmenitic magnetite, 9.9 per cent; diopside, 24 per cent; hypersthene, 2.1 per cent; and olivine, 8 per cent. A hornblendite from northwest of Prospect Lake on Vancouver Island is reported by Clapp[1] to consist of hornblende, 85.2 per cent; augite, 8 per cent; magnetite, 5.5 per cent; and apatite, 1.3 per cent. The chemical analysis of this rock, recalculated in terms of the norm, gives 31.8 per cent labradorite-bytownite, 5 per cent orthoclase, 19.64 per cent diopside, 22.02 per cent olivine, 9.28 per cent magnetite, 3.04 per cent ilmenite, 2.79 per cent apatite, and 3.41 per cent nephelite. The relatively high percentage of apatite shown here is in accord with the composition of many of the hornblendites in southeastern Alaska. These results indicate that the hornblendites may have resulted from the crystallization of a magma of a composition which would usually have produced an olivine gabbro, but which in the presence of a relatively high percentage of mineralizers formed hornblendite.

The basic border facies of many of the stocks and batholiths of the Alexander Archipelago may be explained on the hypothesis of relatively quickly cooled and undifferentiated marginal portions of

[1] C. H. Clapp, "Geology of the Victoria and Saanich Map-Areas, Vancouver Island, B.C.," *Canadian Geol. Survey Mem. 36* (1913), p. 70.

the original magma. But there are locally also marginal pockets of more alkalic feldspathic type, which may perhaps be due in part to the action of mineralizers. The leucocratic sodic types of rock, such as albite diorite and monzodiorite and albite and oligoclase quartz diorite and granodiorite, which are associated in minor amount with each of the similar but respectively more basic and andesine types, apparently have not originated at the same time as the submagmas constituting the major types of rocks, but are due to local causes and processes acting upon the individual submagma itself. The sodic leucocratic types have a composition similar to the aplitic differentiates of the igneous rocks with which they are genetically associated, but they differ from the aplites in having the same grain and texture as the rocks with which they are associated and in occurring as marginal facies or outlying dikes, apophyses, or small stocks, and not as later dikes. They may represent a squeezing out of interstitial liquid from the magma with which they are genetically associated at a relatively late stage in its crystallization, or the direct action of mineralizers may have played a part.

The quartz diorites with relatively low ferromagnesian content, which seem to predominate on Baranof Island, are not readily explained in their relation to the more typical, more highly ferromagnesian quartz diorites of the Wrangell-Revillagigedo belt, and further data are needed.

It is certain that some of the intrusives, the quartz diorites and granodiorites of the Wrangell-Revillagigedo belt in particular, have had their composition locally very considerably modified by reaction with incorporated fragments of schist and sediment. This is also true of portions of the core of the Coast Range batholith immediately adjacent to included or shredded blocks of schist. The resultant variations in composition are in part due directly to the differences in composition of the assimilated rock, and in part indirectly to the same differences because of their effect in prolonging or shortening the period of crystallization of the magma and thus permitting the different degrees of differentiation.

The major features of the variation in composition of the Coast Range batholith cannot be due to differentiation in place. Blocks of schist which extend from the top of the mountains to sea level

would prevent intermovements of the unit or units of differentiation. The grosser features of the batholith must have resulted from successive intrusions toward the east of more highly differentiated magma; or of successive intrusions toward the east of similar magma which was permitted to differentiate to a greater degree as a result of the increasingly higher temperature of the country rock; or to successive intrusions toward the east of increasingly highly differentiated magma, which in turn was enabled to differentiate in place to an increasingly greater extent. The most highly differentiated magma, the granite, does not, however, fall into its proper place geographically, but is found as a late intrusion in the Alexander Archipelago. In the Skagway region[1] there appears to be definite evidence of successive intrusions between the quartz diorite and more siliceous-alkalic types. A great many of the complexities in variation of the batholith appear explicable under the hypothesis of successive intrusions, with varying degrees of differentiation, influenced both by a general rise in temperature of the country rocks as a whole and by local probably markedly cooler portions such as included blocks of schist, and by local reaction with blocks of country rock, including older magmatic facies.

COMPARISON WITH SIERRA NEVADA BATHOLITH

The Sierra Nevada batholith is supposed to have been intruded at about the same time as the Coast Range batholith; a comparison of the two shows extraordinary similarities.

Lindgren[2] makes the following statements regarding the Sierra Nevada batholith:

> The batholiths are not homogeneous bodies, but consist of a great number of separate intrusions; some of them are, however, of gigantic dimensions. In the western foothills of the Sierra Nevada in California smaller intrusions appear which are often quartz diorite, diorite, gabbro, or granodiorite. The main mass is of granodiorite or quartz monzonite; and near the summit region, especially in the Sierra Nevadas, we find smaller intrusions of almost normal granites high in silica with predominating potash. . . . . The intrusions seem to have begun

[1] Adolph Knopf, "The Eagle River Region," *U.S. Geol. Survey Bull. 502* (1912), p. 24.

[2] Waldemar Lindgren, "Igneous Geology of the Cordilleras and Its Problems," *Problems of American Geology* (Yale University Press, 1915), pp. 255–58.

on the west side by irruption of basic magmaperidotites, pyroxenites, and gabbro, and gradually extended eastward, while the composition became more acidic and finally granitic. In any separate intrusion the same succession holds good so that we find basic material near the walls and in embayments while the great masses range from quartz monzonite to quartz diorite.

In order to get an idea of just how closely the analogy between the two batholiths does hold, the writer averaged several groups of analyses of rocks from the Sierra Nevada region, Table III, Nos. 1, 3, 5, and 6, and recalculated the norms, Table IV, Nos. 1, 3, 5, and 6.

There is in general a consistent decrease in the percentage of the accessory minerals, such as magnetite, titanite, and apatite, in passing from the gabbroic to the quartz monzonitic facies. This is true both of the Coast Range and of the Sierra Nevada intrusives.

The rocks in the gold belt of California correspond closely in kind and mode of occurrence to those of the Prince of Wales–Chichagof and Wrangell-Revillagigedo belts in Alaska. The California gold belt granodiorites carry more silica and less lime, magnesia, and ferrous iron than the quartz diorites of Alaska with a similar environment, and in the mode they carry less biotite and more orthoclase. The granodiorite of the core of the Coast Range batholith (Tables III and IV, No. 4) is very similar to the granodiorite of the core of the Sierra Nevada batholith (Tables III and IV, No. 5), and the quartz monzonites of the eastern portion of both batholiths (Tables III and IV, Nos. 6 and 7) are also similar. The quartz monzonite of the Sierra Nevada batholith, such as the Cathedral granite of Yosemite Park, is often very closely porphyritic with large crystals of orthoclase, and the same is true of the quartz monzonite of the Coast Range batholith. In order to obtain a rough idea of the mineral mode of the core of the Sierra Nevada batholith, the writer studied a number of specimens collected along the Merced Valley during a visit in company with a party of the Princeton University Summer School of Geology to the Yosemite Park in 1926. The results give, of course, only the roughest sort of approximation. But they do seem to indicate that the western portion of the core here is on the average a granodiorite, and becomes more alkalic toward the east. They also conform with the chemical analyses in showing a smaller percentage of hornblende and biotite in rock

TABLE III

COMPARISON OF CHEMICAL ANALYSES OF ROCK TYPES FROM THE COAST RANGE AND SIERRA NEVADA BATHOLITHS

	1 Basic Quartz Diorite (Gold Belt, Calif.)	2 Quartz Diorite (Western Portion of Coast Range Batholith)	3 Granodiorite (Gold Belt, Calif.)	4 Granodiorite (Core of Coast Range Batholith)	5 Granodiorite (Core of Sierra Nevada Batholith)	6 Quartz Monzonite (Eastern Portion of Sierra Nevada Batholith)	7 Quartz Monzonite (Eastern Portion of Coast Range Batholith)
SiO_2	57.74	59.55	64.78	64.87	66.74	69.87	70.86
Al_2O_3	17.36	16.18	16.05	16.26	15.98	15.05	14.96
Fe_2O_3	1.95	1.94	1.49	1.51	1.74	1.15	1.06
FeO	4.86	5.61	3.06	2.89	2.21	1.51	1.43
MgO	3.62	2.86	2.13	1.72	1.21	0.74	0.41
CaO	6.81	6.26	4.88	4.72	3.75	2.93	2.23
Na_2O	3.07	3.40	3.49	3.82	3.79	3.04	3.90
K_2O	2.01	2.62	2.43	3.30	3.42	4.76	4.60
H_2O	0.19	0.04	0.20	0.00	0.08	0.20	0.00
H_2O+	1.00	0.82	1.09	0.28	0.53	0.47	0.40
TiO_2	0.81	0.96	0.52	0.70	0.55	0.47	0.34
P_2O_5	0.26	0.26	0.11	0.19	0.20	0.15	0.11
MnO	0.10	.....	0.07	.....	0.09	0.01	.....
BaO	0.09	.....	0.05	.....	0.06	0.11	.....
Total	99.87	100.50	100.5	100.26	100.35	100.46	100.30

TABLE IV

COMPARISON OF NORMS OF ROCK TYPES FROM THE COAST RANGE AND SIERRA NEVADA BATHOLITHS

	1 Basic Quartz Diorite (Gold Belt, Calif.)	2 Quartz Diorite (Western Portion of Coast Range Batholith)	3 Grano-diorite (Gold Belt, Calif.)	4 Grano-diorite (Core of Coast Range Batholith)	5 Grano-diorite (Core of Sierra Nevada Batholith)	6 Quartz Monzonite (Eastern Portion of Sierra Nevada Batholith)	7 Quartz Monzonite (Eastern Portion of Coast Range Batholith)
Quartz	10.54	10.59	20.40	16.98	21.12	26.10	24.72
Orthoclase	11.90	15.57	14.46	19.46	20.24	28.13	27.24
Albite	25.94	28.82	29.34	32.49	31.96	25.68	33.01
Anorthite	27.61	20.85	20.85	17.24	16.40	13.34	9.73
Diopside, Hypersthene, and Olivine	17.06	18.01	11.00	9.53	6.38	4.05	2.72
Titanite	1.98	2.37	1.19	1.78	1.26	1.13	0.79
Magnetite	2.78	2.79	2.09	2.09	2.52	1.62	1.52
Apatite	0.78	0.79	0.35	0.45	0.58	0.46	0.35
Total	98.59	99.79	99.68	100.02	100.46	100.51	100.08

NOTES TO TABLES III AND IV

1. Average of five analyses of basic quartz diorites from the gold belt, Sierra Nevada, California. H. W. Turner, "The Granite Rocks of the Sierra Nevada, California," *Jour. Geol.*, Vol. VII (1899), p. 150.

2. Analysis of composite sample of fourteen specimens from western portion of Coast Range batholith, Alaska. Analyst, J. G. Fairchild.

3. Average of five analyses of granodiorites from the gold belt, Sierra Nevada, California.

4. Analysis of composite sample of six specimens of granodiorite from the core of Coast Range batholith, Hyder district, Alaska. Analyst, J. G. Fairchild.

5. Average of five analyses of granodiorites from the core of the Sierra Nevada batholith, California.

6. Average of five analyses of quartz monzonites from the eastern portion of the Sierra Nevada batholith, California. H. W. Turner, *loc. cit.*, and Adolph Knopf, *U.S. Geological Survey Paper 110*, 1918.

7. Analysis of composite sample of six specimens from the eastern portion of the Coast Range batholith, Hyder district, Alaska. Analyst, J. G. Fairchild.

facies equivalent to those from the portion of the Coast Range batholith discussed here.

The similarity in variation of composition for the Sierra Nevada and Coast Range batholiths must arise from a similar structural cause.

LASANIUS AND THE PROBLEM OF VERTEBRATE ORIGIN

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ABSTRACT

Lasanius, first described by R. H. Traquair in 1898, has since evoked many opinions in regard to both its systematic position and its morphology. On the basis of some new material collected last summer from the Scottish Downtonian, the author has attempted a detailed anatomical reconstruction, and proposed a theory concerning the origin of the visceral skeleton. As the Anaspida are the oldest and most primitive fishlike animals yet discovered, their place in the chain of evolution is exceedingly important. In them we appear to approach nearer than ever before to the connecting link between the vertebrates and the invertebrates.

The material for this study was collected from the Scottish Downtonian during the summer of 1926, at the well-known localities of Birkenhead Burn, Monk's Burn, and Seggholm in Lanarkshire and Ayrshire. My thanks are due to Assistant Director Macgregor and Mr. Tait, of the Scottish Branch of H. M. Geological Survey, for their very kind assistance in the field, and to Dr. Percy E. Raymond for much helpful advice in the laboratory.

Lasanius has been the subject of considerable controversy since it was first described by Traquair.[1] There are two species, *Lasanius problematicus* Traq. and *L. armatus* Traq., distinguished largely by the shape of the dorsal scutes. Orientating them on the basis of a heterocercal tail, Traquair confused the dorsal and ventral sides of both Lasanius and Birkenia, hence these scutes were described by him as ventral in position.

Most of the subsequent investigators accepted Traquair's interpretation, although a few, notably Jaekel, thought that the dorsal and ventral sides might have been confused. The discovery of three Norwegian genera by Kiaer in 1909 definitely settled this point. In his most valuable monograph[2] he has proved, by a detailed study of

[1] R. H. Traquair, "Report on Fossil Fishes . . . . in the Silurian Rocks of the South of Scotland," *Trans. Roy. Soc. Edinb.*, Vol. XXXIX, 1898.

[2] Johan Kiaer, "The Downtonian Fauna of Norway," *Videnskapsselskapets Skrifter. I. Mat.-naturv. Klasse* (1924), No. 6.

cranial structure, that Traquair's figures should be reversed. The median scutes are really dorsal, and the tail has a reversed heterocercal form to which Kiaer applies the name of "hypocercal," a unique form among fishes.

Traquair figured and described his specimens of Lasanius, but made no attempt to interpret their peculiar structures. On the basis of his orientation these were of course exceedingly puzzling. Lasanius did not occur in Kiaer's material, and therefore he undertook no detailed restoration, though he gave much valuable information in comparing it with his three Norwegian genera. Simpson[1] has recently written on the subject, but my restoration and interpretation, based on new material, differs so widely from his that another study of this puzzling form does not seem out of place.

Traquair's figures give a clear idea of the general appearance of this fish, so I will merely summarize here his description. The detailed structure will be described later. Its most striking feature is a series of eight slender, nearly parallel rods, in the anterior part of the animal, springing from overlapping triangular bases. Traquair called these the "post-cephalic rods." There is a set of these rods on each side, pointing forward at an angle of about 45°. Lying under the foremost of the rods is a series of six or seven small cornucopia-shaped "ossicles." Kiaer regards them as marking the position of the branchial openings. Traquair describes a row of eighteen thorn-like dorsal scutes, but figures only seventeen. The shape of the body is probably evenly fusiform and relatively more slender than the other Anaspida, as Traquair showed in his first restoration of 1898. In his second restoration,[2] there is a curious hump back of the head on what he took to be the dorsal side. Simpson's restoration is evenly fusiform, and I likewise agree with Traquair's first restoration. He suggested that the hump is due to oblique pressure, and this is undoubtedly correct. In each of Traquair's figures drawn from specimens that show this hump, the post-cephalic rod-structure from the opposite side lies in a position under its fellow. This com-

[1] G. G. Simpson, "New Reconstruction of Lasanius," *Bull. Geol. Soc. Amer.*, Vol. XXXVII (1926), pp. 397–402.

[2] R. H. Traquair, "Supplementary Report on Fossil Fishes . . . . in the Upper Silurian Rocks of Scotland," *Trans. Roy. Soc. Edinb.*, Vol. XL, No. 33 (1905), Fig. 4.

pact bony mass, on receiving an oblique thrust, would tend to slip out of place, bulging out the body wall, and carrying the skin with it.

STRUCTURAL DETAILS

In most of my material, now in the Museum of Comparative Zoölogy at Harvard University, the post-cephalic rod-structure is more than twice as large as that figured by Traquair, or that indicated by Simpson in his restoration. This apparatus belonged, of course, to a correspondingly larger animal. Consequently, the anatomical details show more clearly than in the smaller individuals. On the figure of a single large specimen, Traquair[1] indicated faint traces of lateral scales. Unusual size and weakly developed scales were not considered by him as details of specific importance, but rather as attributes of a large individual of *L. problematicus*.

The longest of the post-cephalic rods range in different specimens from 7 to 12 mm., measured from the tip to the angle they make with their triangular base. They probably vary according to the age and species of the animal in question. The first four or five are approximately of the same length; beyond, they grow progressively shorter until the posterior rod is 1.0–0.5 mm. shorter than the anterior. The tips are slender and needle-like. Each rod is thickened abruptly at the base, the exterior of which projects outward in a knoblike process. From the inner side, much as the blade of a hoe meets its shaft, a flat strip is directed under the ventral side, joining its fellow similarly projecting from the opposite side.

Each of the rod-bases bears a spine which projects from the knobby process, outside the body, slightly downward and backward. In one case in which this external spine is preserved entire, the length is 4 mm., which is probably a fair average for the rest. Traquair in his first paper[2] showed some of these spines, and Kiaer, in commenting on the pectoral spine apparatus of Lasanius, states that there probably was a row of these spines on either side of the body, in the Norwegian genera. In Pterolepis he found five very small spines issuing from the body behind the large pectoral spine.

[1] *Ibid.*, Plate II, Fig. 8.

[2] "Report on Fossil Fishes . . . . in the Silurian Rocks of Southern Scotland," *Trans. Roy. Soc. Edinb.*, Vol. XXXIX, No. 32 (1898), Figs. 6, 7, 12.

In Lasanius, however, these eight spines are really larger and more powerful than those that Traquair figured, and very much larger than the five little spines of Pterolepis. The pectoral spines of the Norwegian genera, and those of Lasanius, are hollow.

FIG. 1.—Mold of the post-cephalic rod structure of Lasanius, showing the rods of the left side crushed over those of the right. At the right are four of the overlapping dorsal scutes. About 5×.

There is no doubt but that these rods and their bases are subdermal. Heretofore, dermal plates have been found weakly developed only on the sides of large individuals. On an exceptionally well-preserved anterior part of one of my large specimens, faint impressions of long lancet scales are visible in patches. They are ornamented after the manner of those of other Anaspida, with midrib

and fine granulation. The skin covering the post-cephalic rod-structure also bears the thin scales, but too weakly developed there, as well as over the cranium, to give any clue as to structure and arrangement. Furthermore, although exceptionally well preserved

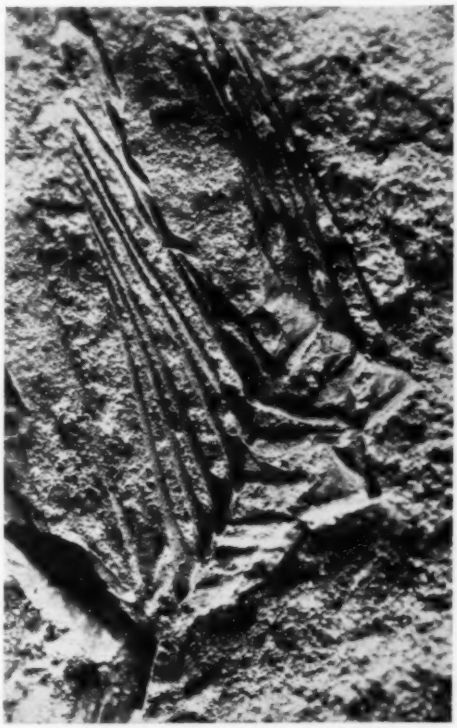

FIG. 2.—Reverse of Fig. 1, showing the hollow bases of the lateral fin spines, and the ventral strips. The branchial ossicles can be seen in position ahead of the foremost rod. About 5×.

in this case, the rods show absolutely no trace of any ornamentation such as would be expected if they were external. The triangular bases, being connected with their fellows on the opposite side, must likewise have been internal. The substance of the rods and their bases was probably cartilage somewhat calcified, combining a fair

degree of stiffness with elasticity. They are preserved as a dense black carbonaceous mass.

The six ossicles marking the branchial openings are more than twice as large as those figured by Traquair[1] and Simpson, but are approximately of the same shape. On an exceptionally well-preserved specimen, a series of fine striations is seen along the center of the broad end of two of these ossicles, and traces of this ornamentation are visible on two others. The thin spinelike anterior end of each ossicle underlies the broad posterior end of its neighbor, the broad end opening in a semicircle toward the anterior post-cephalic rod which overlies it.

The shape of the dorsal scutes was the principal characteristic by which Traquair distinguished his two species. In his restoration he figured those of *L. problematicus*. Simpson says: "These dorsal spines have a less quadrate base, and in general are more like those of Pterolepis Kiaer, both in form and in structure than would appear from previous reconstructions."[2] It is obvious that the scutes that Simpson is describing are those of *L. armatus* and therefore should not be expected to have the shape of those of *L. problematicus*.

The structure of the mouth of Lasanius is not known. Traquair failed to find it in his material, nor does it show in any of my specimens. It was probably of the same general form as that of the other Anaspida, but either the plates forming it were too thin to be preserved, or it was entirely cartilaginous in structure.

The same situation exists with regard to the eye. Traquair was in doubt as to its size and exact position, and represented it in his restoration by a dotted circle. No other details were apparent. My material shows the same spot in the correct position for an eye, with no trace of orbital plates. Simpson drew a large eye with orbital plates, but did not state whether they actually occur in his specimens, or are drawn merely from analogy with the forms described by Kiaer.

GENERAL MORPHOLOGY

Kiaer considered the row of small ossicles to be the boundary of the branchial openings, and this interpretation seems the most logical. Simpson took the same view as regards their function, but

[1] *Ibid.*, Plate V, Fig. 9.

[2] G. G. Simpson, *op. cit.*, p. 400.

thought that they are "not modified scales but sub-dermal structures," making them analogous to the gill arches of higher fishes. The fine striations down the midline of the large semicircular end prove that at least this much of the ossicle must have been external. Simpson homologized these structures with the semicircular ribbing found by Kiaer on the inner side of the branchial band of Pterolepis, and although in Lasanius the semicircular ends are external, they may in the course of time have become subdermal, giving rise to the structures found in the Norwegian forms. Furthermore, Kiaer considered that the branchial band, as he found it in his three genera, must have evolved from several separate elements. The broad end of these ossicles is slightly convex outwardly, which would give the necessary support and clearance to the tube leading from the gills, as it passes through the body wall. There is some evidence that the tapering upper end is bent out of the plane of the broad end. This being the case, the tapering end would be imbedded in the body wall, giving a firmer anchorage for the whole ossicle. The substance of the ossicles, judging by the depth and clearness of the impressions, must have been as stiff as well-calcified cartilage. In some cases the original substance is preserved as a heavy, black, carbonaceous mass.

The post-cephalic rod-structure is the most interesting feature of Lasanius, and it is this unique formation that has been the subject of so much comment and speculation. From the beginning, its functional use has been disputed. Traquair attempted no explanation. Others, notably Abel, have suggested that the rods were branchial arches. Kiaer considered this impossible, and interpreted them as dermal formations homologous to the more specialized pectoral spine apparatus of the Norwegian general. Lasanius is to him the most primitive Anaspid in every respect but one, namely, the number of branchial openings. His main argument is based on his observations of cranial structure in the group, which seems to proceed along the lines of many small plates fusing into a few larger ones.

Dr. Raymond, on the other hand, has never considered Lasanius a primitive form, but rather an active animal that had gone far toward the reduction of the dermal plates found in the other Anas-

pida. The shape of Lasanius, with its relatively slender body and deeply forked tail, is evidence in favor of this view. It is obviously a faster and more powerful swimmer than the thicker-set Birkenia, or any of the Norwegian forms. That specialization took place along the lines of plate-fusion is undoubtedly true in the case of Kiaer's genera. But it is equally conceivable that an active animal, such as Lasanius, can be as highly specialized along the lines of plate reduction. Furthermore, the post-cephalic rod-structure follows the same course as the long, lateral, list-shaped plates described by Kiaer in the other Anaspida, the angle at the base conforming with the angle made by the ventral with the lateral scale system. Kiaer showed that the list-shaped plates follow the course of the myotomes, therefore the rod-structure, together with its base, having the same course, must be conceived of as doing likewise. The fact that the dorsal scutes are equally strongly developed in Lasanius and in the armored Anaspida gives additional weight to the theory that Lasanius was once armored. It will be remembered that the rod-structure is internal, and therefore if it is not a specialization of certain of the list-shaped dermal plates, the coincidence is indeed remarkable. This point will be discussed in greater detail below. If then we have an active animal exceedingly fishlike in form, that may legitimately be regarded as specialized for swimming, we should expect to find anatomical details which would throw some light on the morphology of the higher fishes. It seems to me, therefore, that in this structure we have the earliest evidence concerning the origin of the visceral skeleton. They are probably not gill arches, as Abel supposed, but are in a stage prior to the formation of the true gill arch. In reviewing the evidence for this theory, let us take the immediate ancestor of the family as a point of departure.

In discussing this family as a possible ancestor of the vertebrates, Dr. Raymond takes the position that the heavily plated members of the family possessed no notochord, or any other internal skeleton.[1] The fairly rigid exoskeleton, with the scales rabbeted together, would be sufficiently strong to furnish attachment for the muscles. Kiaer, on the other hand, considered that these animals did possess

[1] P. E. Raymond, "The Anaspida and the Problem of the Origin of the Vertebrates," *Amer. Jour. Sci.*, Vol. X, 1925.

a notochord, although he was unable to find the slightest trace of one. A curious lump, not unlike a primitive brain in general outline, appears in some of my material of Lasanius, near the dorsal side of the head. This protuberance is apparent in most of Traquair's figures, in both publications, though he makes no comment upon it. In one well-preserved specimen, a dark carbonaceous line, in some parts slightly raised, comes from the posterior end of this protuberance and runs along the dorsal side for about 15 mm. Could this be a primitive notochord attached to a cartilaginous braincase?

Be that as it may, we will postulate our immediate ancestor as a form covered with dermal plates, carrying dorsal scutes, and having moderately developed lateral spines, which in all probability supported a fin membrane. Kiaer considered the pectoral spine apparatus of the Norwegian genera homologous with pectoral fins, and that its origin was in paired, ventral fin folds. From this common ancestor we have two lines of evolution, one culminating in Rhyncolepis and the other in Lasanius. In the former, the lateral spine structure evolved into the specialized pectoral spine apparatus with a loss of the posterior spines, whereas in the latter the spines became longer and more powerful, with a strong set of basal supports tied ventrally. In fact, Pterolepis, the most primitive of the Norwegian forms, shows vestiges of five spines behind the postbranchial plate and pectoral spine.[1] I think it can be taken as a certainty that neither Birkenia nor the three Norwegian genera possessed any such structure as that of Lasanius. Large and bulky, and of so firm a construction that the individual rods are very rarely found separated, its presence could not fail to have been noted in fragmentary specimens had it been present. The lateral spines, being really fin supports, would require a firm anchorage. Hence the base would tend to grow in size, and fuse with the list-shaped dermal plate lying directly above it. As all active animals tend to reduce their armoring, the plates in this line become lighter with the exception of the list-shaped plates lying above each fin spine. These escaped the general reduction of dermal armor, because of their acquired function as basal fin supports. In the course of time

[1] Kiaer, *op. cit.*, Fig. 31*b*.

these rods were drawn under the surface and became subdermal, much as certain bones of the skull and pectoral girdle are known to have had a dermal origin. Lasanius probably possessed a notochord, but its sheath must have been absolutely uncalcified, or some definite trace of it would have been found in a form having so thin a body covering. The post-cephalic rod-structure is probably fairly well calcified, therefore the notochord must have been a more recent acquisition. The fact that the other Anaspida possessed no such post-cephalic rod-structure adds to the weight of negative evidence against their having had a notochord at all. If it can ever be definitely proved that the plated Anaspida had no notochord, it will be practically conclusive evidence in support of this theory of the evolution of Lasanius.

An alternative to this theory would postulate the immediate ancestral form as unarmored. In that case the rods would be explained as having arisen internally, as basal fin supports, analogous in form and structure to the basal supports of dorsal and anal fin rays found in certain Teleosts, such as carp and perch. It is true that most morphologists draw a sharp distinction between membrane, or dermal, bones and cartilage bones, and that the visceral skeleton is considered as belonging to this latter, or endoskeletal, group. Nevertheless, although now pre-formed in cartilage, there is no evidence which positively precludes the possibility that the visceral skeleton might originally have had a dermal origin. Whichever its mode of origin, it will be remembered that these post-cephalic rods, their bases, and the ventral strips correspond exactly to the courses of the long list-shaped scales of the other Anaspida. The angle that the rod makes with its ventral strip corresponds to the angle that the lateral scale system makes with the ventral. As I have said above, Kiaer considers that these scales follow the course of the myotomes. Therefore, the post-cephalic rod-structure, whether we accept for it a dermal or an internal origin, must have developed along the same course.

As the pectoral fin membrane acquired greater importance, the basal supports likewise grew, and were already tied to their fellows on the opposite side. The pectoral fins had acquired considerable swimming importance as we find them in Lasanius. The post-

branchial plate and pectoral spine apparatus of the other Anaspida are the degenerate remnants of the structure that gave rise to the post-cephalic rod-structure in Lasanius, before it became internal. Thus we have this well-knit structure probably of a semicalcified cartilage placed just behind the branchial region, a position in which such an apparatus could not help acquiring some secondary function in the life of the animal.

I think we may take for granted, as a result of Kiaer's investigations, that, like the Cyclostomes, the Anaspida possessed pouch gills. Can we therefore assume that this subdermal rod-structure is homologous with the branchial basket possessed by the modern group? One objection is of course that the branchial openings, as marked by the row of six ossicles, would lie in front of the gill pouches themselves. In the modern Cyclostomes, Myxine, and Bdellostoma, the outlets have a backward trend, in the former converging into a common tube which discharges far behind the posterior gill pouch. A forward discharge is not inconceivable as the primitive condition of pouch gills, later modified to a backward, because it proved poorly adapted to the conditions of water living. Discharge in the direction in which the animal swims would obviously not be as efficient as a backward-directed stream. The branchial basket of Cyclostomes is of course a highly specialized structure; therefore no detailed resemblance to the post-cephalic rod-structure of Lasanius is to be expected. Nevertheless, a certain similarity of function must be assumed. The sixteen internal rods, with their powerful overlapping bases fastened together ventrally, strengthened the body wall to a very considerable degree. The two anterior-most rods, at least, are close enough to the line of six ossicles to have served as a protection for the pouch gills.

Very little modification would be needed to change this internal structure of Lasanius into a sort of branchial basket, or more properly into a series of gill arches, somewhat of the type found among the Elasmobranchs. Furthermore, like true visceral arches, these rods are tied ventrally by flat strips, probably of cartilage, whereas they remain unattached dorsally. Morphological evidence goes to show that the visceral skeleton probably once contained more than seven elements. Here we have eight, and if we include

the row of ossicles, nine. Dr. Raymond recently proposed an ingenious hypothesis in this connection. As the Anaspida have no true mouth and jaws, we have in them a condition previous to the specialization of the visceral skeleton. Consequently, all its elements are intact. The first pair of rods, after passing through the gill-arch stage, may have eventually become the jaws; the second pair, the hyoid arch; the next five, gill arches; and the last pair, which in Lasanius is by far the smallest, may have gradually lost functional importance, and either disappeared or become a vestige,

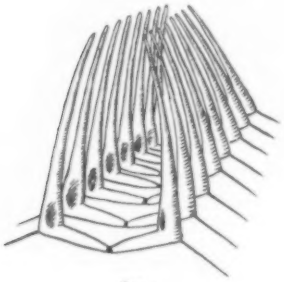

FIG. 3

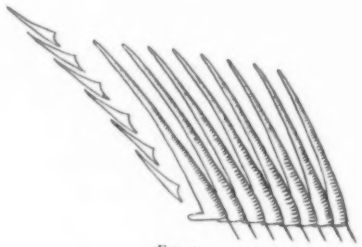

FIG. 4

FIG. 3.—Restoration of the post-cephalic rod structure of Lasanius. Note the general resemblance to the gill arches of modern Elasmobranchs. About 5×.

FIG. 4.—Side view of Fig. 3, showing the angle of the rods. The branchial ossicles are in position. About 5×.

such as the spiracular cartilage is thought to be. The anatomy of modern Elasmobranchs proves that this has been the development of the visceral skeleton, from the stage when all the arches were similar.

In brief, then, we have first either the dermal origin of these rods, from specialized list-shaped dermal plates, or else their direct internal origin as fin-spine basals. Second, whichever their origin, as the lateral fin membrane grew in size, the basal spine supports became correspondingly longer and heavier, until, by virtue of their particular position, they also helped very materially to strengthen the body wall, and to protect in some measure the gill pouches, and probably also the viscera. Lastly, this structure migrated forward, and became the primitive visceral skeleton, with all

of its arches similar. The later specializations that this skeleton is known to have undergone require a greater modification and rearrangement of its parts than would the modification of the postcephalic rod-structure of Lasanius into primitive gill arches.

THE CAUDAL FIN

As Kiaer has conclusively demonstrated, these fishes possess a reversed heterocercal tail, a form hitherto unknown among fishes. In discussing its origin, he considered that it more probably arose from the protocercal than from the heterocercal. For this conclusion it is necessary to accept as a premise that the protocercal, or so-called "primary diphycercal," is the most primitive of all tail forms. Embryology is of course the mainstay of this latter contention, but it is a fact worthy of note that in all cases in which this type of tail occurs in the adult form, the fish in question can more properly be regarded as highly specialized rather than primitive. As the Anaspida are the oldest animals so far discovered that really have a fishlike form, there is nothing with which to draw a fair parallel. The heterocercal tail appears in the Ostracoderms, but, being highly specialized bottom grovelers, they can bear only indirectly on the problem.

Although a hypocercal tail is a unique form, it need not necessarily be regarded as a barrier to the position of the family on, or near, the main stem of the fishes. It is, on the other hand, rather a form we might expect to find in a primitive group, either lacking or just developing a notochord. If such a notochord were present, it must have been at a very early stage of development, and therefore thin, with absolutely no trace of calcification in the sheath. The anterior end of the body would be at, or near, the specific gravity of water, because of the visceral and branchial cavities. Any necessary adjustment could easily be taken care of by the balancing action of the pectoral fins. The posterior end, composed of solid muscle, plus the weight of the caudal fin rays, would have a specific gravity slightly greater than water, hence it would tend to droop, lacking either a thick or a calcified notochordal sheath. In an invertebrate the case would be even better. Starting with a downward trend of the axis of the body, the caudal lobe must develop on the upper side in order

to be mechanically efficient. A fish in swimming lashes its tail from side to side, with a stroke resembling sculling with an oar. The posterior part of the body is bent into a curve, then rapidly extended. The plane of the caudal fin is kept normal to the major axis of the body. It is during the extension stroke that the fish gets its driving force, and in order to receive this thrust most efficiently, the caudal fin should be as nearly as possible in line with the major axis of the body. It can readily be seen that, given a body axis with a downward trend, a caudal lobe on the under side would throw the caudal fin out of line and, in addition, ruin the stream-line effect of the body as a whole. In this case, therefore, the hypocercal tail is the only efficient shape.

Dr. Raymond has suggested to me that the hypocercal lobe is really the dorsal fin which developed back of its normal position, because of the row of dorsal scutes. It seems to me, however, more reasonable to regard it as a purely mechanical response to the needs of this particular form of body.

THE UNPAIRED NASAL OPENING

Kiaer regards the unpaired nasal opening as the most important single characteristic possessed by the Anaspida, and uses it as positive evidence of their relationship to modern Cyclostomes. To neither Dr. Raymond nor myself does this seem particularly convincing, when considered from the point of view of brain structure. Modern Cyclostomes, although possessing only one nasal opening, have two widely separated olfactory lobes, each with its olfactory tract and nerves. The paired nerves unite anteriorly in a common olfactory bulb. It is obvious that the immediate forerunner of such a brain must have been of the diplorhine type, and that the single nasal opening is a secondary feature. In this connection it will be remembered that the respiratory mechanism of this class is highly specialized. Not only may both inspiration and expiration take place through the external gill apertures, but when the mouth is occupied, the inspiratory current may enter through the nasal opening.

On the other hand, the brain of Trematapis described by Wiman,[1] which Kiaer regards, from the position of the surficial

[1] C. Wiman, "Über Gehirn und Sinnesorgane bei Trematapis," *Bull. Geol. Inst. Upsala*, Vol. XVI, 1918–19.

openings, as similar in form and development to that possessed by the Anaspida, shows a very different structure. Here there is no separation into two olfactory lobes and tracts. It is a unit, with no suggestion of a division. The tip of this prolonged forebrain reaches the olfactory pit. This should be a true monorhine, and the head shield shows but one nasal opening. Ascending higher in the stratigraphic series we have next the brain of *Rhadinichthys deani* Eastman, a ganoid from the base of the Waverly of Kentucky.[1] Here the forebrain is double, but the two parts lie side by side in a prolonged process ending in a common protuberance which is probably the olfactory bulb. Some doubt exists as to whether this prolonged forebrain consists of the olfactory tracts or is really the primitive lobes. If the former, then the true lobes lie in the badly preserved region called the "thalamus." This is also true of the brain described below.

Another fish brain has been described from the Pennsylvanian near Lawrence, Kansas.[2] The so-called "olfactory lobes" lie ahead of the optic lobes in a prolonged forebrain, which tapers into the "olfactory tracts." The general form resembles that of the Trematapis brain, but in these fishes the anterior process has a distinct median groove, showing that a tendency toward paired lobes and tracts was well under way. Moodie is in doubt whether or not the olfactory tracts are incomplete. If incomplete, the tracts may have divided ahead of their present terminus, and the olfactory bulbs are lacking. If complete, the region called "olfactory tracts" may be a primitive form of olfactory bulb. Moodie inclines more toward the latter point of view. In either case the brains show a distinct monorhinal tendency.

Briefly, the evidence of these three brains seems to show, first, that the Cyclostomes are not fundamentally monorhinal in the same sense that Trematapis is, and that the Anaspida together with the monorhinal Ostracoderms cannot be placed in their group; second, that these two Palaeoniscid brains, although they probably had two olfactory tracts, seem to show a single lobe, and therefore

[1] C. R. Eastman, "Devonian Fishes of Iowa," *Geol. Survey of Iowa*, Vol. XVIII (1907), p. 264.

[2] R. L. Moodie, "A New Fish Brain from the Coal Measures of Kansas, with a Review of Other Fossil Brains," *Jour. Compar. Neur.*, Vol. XXV, No. 2, 1915.

may have arisen from the monorhinal type; and lastly, that the Anaspids therefore are not necessarily precluded from being ancestral to a diplorhine line of fishes.

PLACE IN EVOLUTION

The systematic position of the Anaspida has been discussed from many different angles, and it is not my purpose to enter far into this controversy. A. S. Woodward considers them as a group

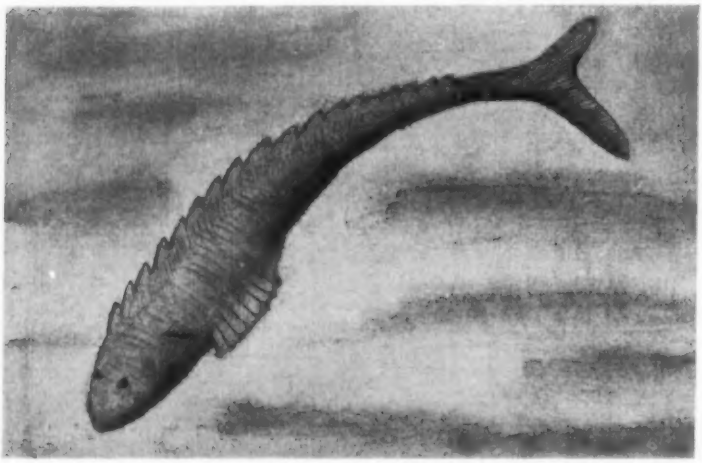

FIG. 5.—New restoration of a large specimen of *Lasanius problematicus* Traq. based on all available material. Slightly smaller than natural size.

under the Ostracodermi.[1] In his presidential address before the Linnean Society, he spoke of the Anaspida as probably being "the latest survivors of the ancestral Ostracoderms, which were beginning to acquire a hard dermal skeleton at the end of Silurian time."[2] Their relationship to the Ostracoderms is proved by their similarity in brain structure, as inferred by Kiaer from the external openings, and, as Woodward has suggested, the two lines undoubtedly had a common ancestor. The Ostracoderm line led to a blind alley, and

[1] *Eastman-Zittel Text Book of Paleontology*. London, 1902.

[2] "Presidential Address," *Proc. Lin. Soc. London*, 1920.

such too may have been the fate of the more heavily plated Anaspida, but it is not impossible that Lasanius may have given rise to a line of primitive "Ganoids." Having lost its old, and apparently structureless, plates, it would be in a position to acquire those of the ganoid type. The hypocercal tail could be transformed by changes in the center of gravity, such as Schmalhausen has proposed,[1] or by the thickening or calcification of the notochordal sheath. In this connection it will be remembered that the dorsal musculature of a fish is stronger than the ventral, and this, coupled with a stronger notochordal sheath might have helped to give it its first heterocercal trend, which later resulted in a permanent curvature of the spinal column. The caudal fin of some Crossopterigians, for instance Osteolepis, though technically heterocercal, is not as truly such as is that of sturgeons or sharks.

Although this group throws very little immediate light on the major problems of vertebrate ancestry, future discoveries may very possibly prove them to be the connecting link between the ancestral invertebrate and the true fishes. Their present importance lies in the fact that they can be interpreted as the most primitive fishes so far discovered, and therefore should be counted on to furnish clues as to the morphology of the higher types. This alone constitutes them one of the most important paleontological discoveries of recent years.

[1] J. J. Schmalhausen, *Zeitschr. wiss. Zoöl.*, Vol. CIV, 1913.

A SUGGESTION FOR THE SIMPLIFICATION OF FAULT DESCRIPTIONS

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ABSTRACT

Descriptions of faults may be simplified by giving the amounts of the three components of the movement of one side relative to the other parallel to each of three mutually perpendicular axes. The axes here suggested are (1) the direction of strike of the fault plane, (2) the horizontal direction of dip of the fault plane, and (3) the vertical.

INTRODUCTION

Perhaps in no part of geological literature is there so much confused terminology as in the nomenclature of faults. It was in recognition of this state of affairs that a special committee was appointed by the Geological Society of America for the purpose of agreeing upon and defining a fault nomenclature to be of general use to the geological profession. The work of this committee is very commendable in that terms were agreed upon and well defined.[1] It seems to have failed in a sense, however, in that the terminology presented is so complicated that few geologists succeed in remembering the definitions. Consequently many geologists continue to use their own preferred terminologies, and other geologists, not knowing those preferences, are not always able to tell exactly what is meant.

It seems evident that something needs to be done to eliminate this confusion. Since mathematics and physics have long since solved similar problems in three dimensions in a satisfactory manner, the writer feels justified in borrowing their solutions and applying them to the geological problem of faults.

PROPOSED METHOD OF DESCRIPTION

To begin, let us suppose, as a working definition, that a fault is a plane in the lithosphere parallel to which there has been differential

[1] "Report of Committee on Nomenclature of Faults," *Bulletin Geological Society of America*, Vol. XXIV (1913), pp. 163–86.

movement of the rock masses on the opposite sides. The problem, then, will be to find some simple and accurate method of specifying the orientation of the fault plane and the direction and magnitude of the movement along the plane, or of its components.

It is self-evident that a fault plane may have any conceivable orientation with respect to some given plane, as, for instance, the horizontal plane. It is equally evident that from a given point on this plane, the movement parallel to the plane may have any direction in an arc of 360 degrees and any magnitude within certain wide limits. Hence, any formulation of fault movements in general will necessarily involve a problem of positions, distances, and directions in three dimensions, or space. Since all positions, directions, and distances are relative, we must first choose arbitrarily some point and three directions to which every other point must be referred in order to define its position.

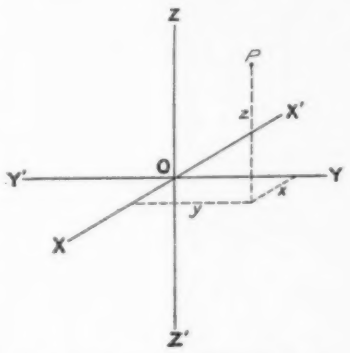

FIG. 1.—Point *P* is defined by the distances *x*, *y*, and *z* parallel to the axes *X*, *Y*, and *Z* respectively.

For the purpose of defining the movements and directions involved in a given fault at a given place, the system of rectangular co-ordinates, which is familiar to all who have studied so much as elementary college mathematics or any physics that involves problems of space, seems best adapted. This system consists of three mutually perpendicular axes corresponding to three arbitrary directions of reference and intersecting at a point corresponding to some known point of reference. These are the familiar *X*, *Y*, and *Z* axes of analytical geometry. Given these, any other point in space may be definitely located by stating its distance from the known point, or origin, parallel respectively to the three axes *X*, *Y*, and *Z* (Fig. 1).

In order to apply this method to faults, we must first define our three directions of reference. It would be easily possible to use the

natural system of compass points and the vertical direction, in which we could let the *N–S* line be one horizontal axis, the *E–W* line be the other horizontal axis, and the vertical line through the intersection of these two form the third axis. These are the axes to which all faults are by present usage ultimately referred, but because of precedence and for purposes of simplicity it seems better to use reference directions more directly related to the fault, and then refer them, in turn, to the axes above.

The most commonly used reference directions related directly to faults, and perhaps the best for our purposes, are (1) the strike of the fault plane, which is by definition the line of intersection of

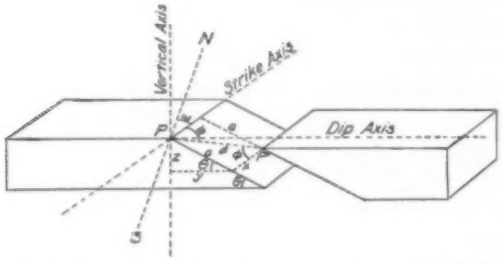

FIG. 2.—The components of movement *x*, *y*, and *z* are sufficient to define the fault movement.

the fault plane with a horizontal plane; (2) the horizontal line in the direction of the dip of the fault plane; and (3) the vertical line through the intersection of these two. Hence the primary axes would be the strike direction, the dip direction, and the vertical, all intersecting at a point on the fault plane whose relation with the *N–S* line will be defined by the angle that its strike makes with that line.

Let us assume a fault (Fig. 2) about which everything is known. We shall assume that the side underneath the plane has remained stationary and that the other side has moved relatively to it. Let some point, *p*, be a point of origin on the stationary side, and let *p′* be a point on the opposite side which was adjacent to *p* before the movement took place, but has been displaced a distance, *d*, from *p* by the movement along the fault plane. Then our strike, dip, and vertical axes will intersect at the point *p*, and will be at a horizontal

angle of ω degrees from the N–S line. Suppose that the point p' moved NE. and downward along a path which makes an angle, ϕ, with the strike axis which goes through p. Let x be the component of this movement parallel to the strike.

Let y be the component parallel to the dip axis.

Let z be the component parallel to the vertical axis.

Let θ be the angle of dip of the fault plane.

Then all the components x, y, and z, and their resultant, d, may be found if the angles ϕ and θ are known along with any one of the distances, x, y, z, or d.

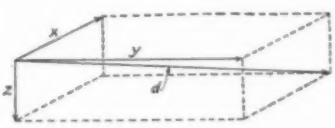

FIG. 3

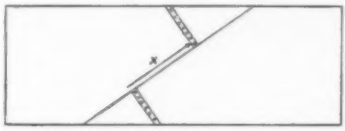

FIG. 4

FIG. 3.—Diagram showing the resolution of vector quantities in three dimensions where d is the resultant of the components x, y, and z.

FIG. 4.—Areal plan showing component x when vertical dike lying in plane of vertical and dip axes is cut.

If we let a be the perpendicular from the point p' to the line of strike through p, then we may show the following relations between x, y, z, and d and the angles ϕ and θ:

$$x = d \cos \phi$$
$$a = d \sin \phi$$
$$y = a \cos \theta = d \sin \phi \cos \theta$$
$$z = a \sin \theta = d \sin \phi \sin \theta$$

By the method of vector analysis, the resultant, d, of three mutually perpendicular components, x, y, and z, is equal to the diagonal of the rectangular solid whose sides are x, y, and z. Hence:

$$d^2 = x^2 + y^2 + z^2 \quad \text{(see Fig. 3)}.$$

In general, if we know the direction and magnitude of movement along a fault plane, then it is possible to express that movement in terms of its components parallel to its strike, dip, and vertical directions. If the direction of the movement is known, but not the

magnitude, then the direction may be expressed by the angles ϕ, which the fault striae make with the line of strike, and θ, which is the dip of the fault plane.

Thus it will be seen that, in order to describe a fault movement completely, it will be necessary only to give the amounts and directions of the movement of one side relative to the other, parallel respectively to the strike, dip, and vertical directions, thus:

Strike of fault plane	N. ω E.
Dip of fault plane	SE. θ
Movement SE. side	Strike, x ft. NE. Dip, y ft. SE. Vertical, z ft. down

In case the plane of the fault were vertical, it is obvious that the dip component would be zero. If it were horizontal, there would

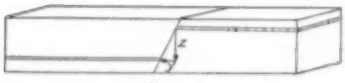

FIG. 5

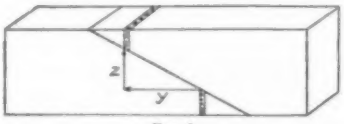

FIG. 6

FIG. 5.—Components y and z shown when fault cuts a horizontal bed.

FIG. 6.—Components y and z determined by dike or bed parallel to strike and vertical axes.

be no strike, so that the *N*–*S* and the *E*–*W* lines would become the horizontal axes.

Should there ever be general agreement upon this method of description, it would be possible to establish conventions to give the same information in shorthand style. For the present its chief virtue lies in the fact that it enables one to give his fault descriptions in terms which are certain to be understood. Another advantage is that it might encourage the field man to make his fault calculations while he is still in the field. He will then know if any necessary data are lacking while it may still be possible to obtain them. This may also assist many geologists, who are already describing faults completely in three dimensions by means of word descriptions, in avoiding being misunderstood. It is hoped that a simplified means of fault description will encourage the displacement of the incomplete

two-dimensional system of fault description, still too commonly used, by a complete three-dimensional description.

It would be futile to attempt to work out theoretically all the possible combinations which might occur in the field from which the three components of the fault movement might be calculated. Every fault will of necessity be a problem all its own to tax the skill and ingenuity of the observer. It is important to note, however, that no data can define a fault movement if they are insufficient for the calculation of the three components. Suffice it to add that if any distinguishable plane such as a dike, sill, bedding plane, or another fault lies parallel to any two axes and has been cut by the fault considered, then the component of the movement along the third axis would be equal to the perpendicular distance between the displaced parts of the broken plane (Figs. 4, 5, and 6).

In conclusion, this suggestion is an attempt to express only in established terminology what has heretofore been expressed in a terminology not generally accepted or understood.

ON THE USE OF THE TERMS "DIABASE" AND "DOLERITE"

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ABSTRACT

The terms "diabase" and "dolerite" are used with various meanings in different countries. In this paper the development of the terms is traced.

Certain rocks, thought to be composed essentially of grains of amphibole, chlorite, and feldspar, were called *Grünsteine* by Werner[1] and Haidinger.[2] Brongniart[3], who did not like this word, in 1807 substituted for it "diabase" (διάβασις, "a crossing over"), and of all the terms proposed by him in his book, this and one other were the only two retained in his new classification of 1813.[4] Writing in 1819, d'Aubuisson said: "M. Haüy a dernièrement donné à cette même roche le nom de *diorite*,"[5] but Haüy[6] himself did not publish this until 1822. In 1827 Brongniart[7] himself abandoned the term "diabase" in favor of "diorite," for he considered it "utile à la science de diminuer autant que possible les synonymes qui fatiguent la mémoire et jettent de l'incertitude dans les déterminations." With this, therefore, the original term "diabase" became obsolete.

In 1835 Gustav Rose[8] showed that the principal dark constituent

[1] A. G. Werner, *Kurze Klassifikationen und Beschreibung der verschiedenen Gebürgsarten*, Dresden, 1787.

[2] Carl Haidinger, *Entwurff einer systematischen Eintheilung der Gebürgs-Arten* (Wien, 1787), p. 49.

[3] Alexandre Brongniart, *Traité de minéralogie* (Paris, 1807), Vol. I, p. 456.

[4] "Essai d'une classification minéralogique des roches mélangées," *Jour. de Mines*, Vol. XXXIV (1813), p. 33.

[5] J. F. d'Aubuisson de Voisins, *Traité de géognosie* (Strassbourg, 1819), Vol. II, p. 146.

[6] L'Abbé Haüy, *Traité de minéralogie* (Paris, 1822), Vol. IV, p. 540.

[7] Alexandre Brongniart, *Classification et caractères minéralogiques des roches* (Paris, 1827), p. 80.

[8] "Über die Grünsteine," *Pogg. Ann.*, Vol. XXIV (1835), p. 1.

of many *Grünsteine* consists of pyroxene and not of hornblende, and that the other component is labradorite or oligoclase (andesine of our modern classification). For these augite-plagioclase-chlorite rocks, Hausmann,[1] in 1842, adopted the abandoned name of "diabase." Naumann[2] said, in 1849, that if the feldspar of these rocks should prove in all cases to be labradorite, the rocks should be united with the gabbros.

In 1853 Senft[3] still used the term "diabase" for granular augite, chlorite, and labradorite or "oligoclase" rocks. Von Cotta,[4] in 1862, separated his *Grünsteine* into three divisions: diabase, consisting of feldspar, augite, and chlorite; gabbro, consisting of feldspar and pyroxene; and diorite, consisting of acid plagioclase and amphibole. The "augite" of the diabase he found to be hypersthene or less commonly augite, while the feldspar was oligoclase (i.e., andesine) or labradorite. The chlorite was recognized as secondary. In the gabbro the feldspar was given as labradorite or saussurite, and the pyroxene as diallage, smaragdite (uralite, actinolite), and (or) hypersthene.

Zirkel[5] was the first to use the name "diabase" for a pyroxene and labradorite rock, for he found that in the great majority of cases, analyses showed the plagioclase to be labradorite. He described the rock as of coarse to fine texture, and as occurring in sheets or dikes. The chlorite he regarded as secondary.

In 1877 Rosenbusch[6] introduced the age factor when he defined "diabase" as a pre-Tertiary rock, consisting essentially of augite and a plagioclase which generally is basic and occurs in lath-shaped crystals. The rock may be fresh or altered. The mode of occurrence is in dikes, sheets, or flows. Chlorite, mentioned as an essential mineral by some of the other writers, he regarded as secondary. In 1877 he[7] defined "diabase" as an "intrusive" rock, occurring in sills or dikes,

[1] J. F. L. Hausmann, *Über die Bildung des Harzgebirges* (Göttingen, 1842), p. 18.

[2] Carl Friedrich Naumann, *Lehrbuch der Geognosie* (Leipzig, 1849), p. 591.

[3] Ferdinand Senft, *Die Felsarten* (Breslau, 1857), pp. 60, 253.

[4] Bernhard von Cotta, *Die Gesteinslehre* (Freiburg, 1862), pp. 82–93.

[5] Ferdinand Zirkel, *Lehrbuch der Petrographie* (Bonn, 1866), Vol. I, p. 78.

[6] H. Rosenbusch, *Mikroskopische Physiographie* (Stuttgart, 1877), Vol. II, p. 323.

[7] *Ibid.* (2d ed., 1887), Vol. II, pp. 173–74.

usually old but in many cases of comparatively recent age, and having a hypidiomorphic-granular texture. In 1896 he[1] said that the rock may be extrusive or intrusive; may occur in sheets, sills, or dikes; has a hypidiomorphic-granular or intersertal-porphyritic texture; and is usually of early Paleozoic age although some quite recent varieties are found. The mineral combination in the definition remained augite and basic plagioclase. In his *Elemente*,[2] in 1898, he said the texture is characterized by the want of a recurrence of any mineral in two generations, giving the diabasic-granular or ophitic texture (p. 325). He now divided his basaltic rocks into three groups (p. 304): basalts were the Tertiary and recent members of the family, melaphyres chiefly Carboniferous or Permian, and diabases early Paleozoic. He added, however: "Doch hat sich die Altersunterscheidung zwischen Melaphyr und Diabas in den letzten Jahrzehnten mehr verwischt, so dass man von Mesodiabasen u.s.w. gesprochen hat."

The use of the term "diabase" by the United States Geological Survey[3] is indicated by a circular issued in 1897. "Diabase has an ophitic texture. This texture may be megascopic or microscopic. The mineral constituents are those of gabbro. Diabase commonly occurs as dikes and [*sic*] sills."

In the meantime in England Allport,[4] in 1874, had determined to drop the term "diabase," for, having found chlorite in all the so-called diabases which he had examined, he said the rocks were simply altered dolerites. "I propose to discontinue the use of the terms Melaphyre, Aphanite, Diabase, and Greenstone, and suggest the desirability of including all the basic augitic rocks in one group under the generic name *Dolerite*." He wished to retain the term "basalt," however, for in a footnote (p. 530) he said: "Strictly speaking, there should of course be only one name for these rocks, as coarse- and fine-grained varieties occur in one and the same mass;

[1] *Ibid.* (3d ed., 1896), Vol. II, p. 1094.

[2] *Elemente der Gesteinslehre* (Stuttgart, 1898), pp. 304, 325.

[3] Unpublished circular, Committee on Nomenclature of Igneous Rocks, May 27, 1897.

[4] S. Allport, "On the Microscopic Structure and Composition of British Carboniferous Dolerites," *Quart. Jour. Geol. Soc.* (London, 1874), Vol. XXX, pp. 529–67, in particular pp. 529–30.

the term basalt, however, is so well known and generally used that it is not likely to be discontinued." His usage, therefore, is "basalt" for the fine-grained extrusives and "dolerite" for the coarse-grained.

This use of the word "dolerite" and the limiting of "diabase" to decomposed rocks only gradually grew in England. It was used by Teall[1] in 1888, but Harker[2] in 1902 still considered diabases as "*intrusive* bodies of hypabyssal pyroxenic rocks." He considered them equivalent in composition to gabbro but characterized by their ophitic texture (p. 134). He also said (p. 131) that "some English writers have inconveniently employed the name diabase for a more or less decomposed dolerite." Later, however, Harker[3] substituted "dolerite" for "diabase" in his definition, otherwise word for word the two are identical. The mode of occurrence, as before, is in dikes, sills, and laccoliths. Of diabase he now said that it is in part synonymous with "dolerite," but regarded the word as objectionable, and dropped it.

This, then, seems to be the modern English usage, for Holmes quite recently said:

> For a time the term *diabase* was applied to pre-Tertiary dolerites, and since, especially in Britain, such rocks are frequently altered, the term has come to mean an altered dolerite in which the feldspars are saussuritized or albitised, or the pyroxene more or less replaced by hornblende or chlorite.[4]

Also:

> In a general way dolerite is distinguished from basalt by its coarser grain and the absence of glass; specifically by . . . . its holocrystalline character and the development of ophitic texture. In practice, however, there are many cases in which it is difficult, if not impossible, to make an unequivocal choice between the terms *basalt* and *dolerite*, since there is not, and cannot be, any definable line drawn between them. As field-terms, however, these names are generally restricted to extrusive and intrusive rocks respectively.[5]

Before comparing the usages in the different countries, it is necessary to go back and trace the meaning of the word "dolerite,"

[1] J. J. Harris Teall, *British Petrography* (London, 1888), p. 136.

[2] Alfred Harker, *Petrology for Students* (3d ed.; Cambridge, 1902), pp. 130–39.

[3] *Ibid.* (4th ed.; Cambridge, 1908).

[4] Arthur Holmes, *The Nomenclature of Petrology* (London, 1920), pp. 78, 83.

[5] The actual use of the terms "basalt" and "diabase" in the United States is practically that of the English field use of "basalt" and "dolerite."

for its use in the English sense has brought confusion in the literature.

The term "dolerite" (δολερός, "deceptive," since it was impossible megascopically to distinguish it from "diorite") was invented by Abbé Haüy some time prior to 1819, in which year it was mentioned by d'Aubuisson. "L'aphanite est un mélange de feldspath et d'amphibole à l'état compacte; la dolérite compacte est, de son côté un pareil mélange de feldspath et d'augite."[1]

TABLE I

Country	Intrusive (with Ophitic Texture)	Extrusive			
		Coarse	Fine	Paleozoic	Altered
United States.	Diabase (modern use)	Basalt	Basalt	No age classification used	No special name
Germany.....	Diabase, by Zirkel, 1866	(Dolerite*)	Basalt	Diabase (Rosenbusch)	†
Great Britain.	Diabase by Harker, 1902; dolerite by Harker, 1908‡	Dolerite generally; Allport, 1874§	Basalt	No age classification used	Diabase (general usage)

* Not in common use at present.

† "Diabase" is often used for the altered rocks, primarily because the Paleozoic rocks are usually so altered.

‡ The English field use, according to Holmes, for these intrusive, ophitic rocks is "diabase." Harker, 1902 and 1908, says these rocks occur as dikes, sills, and laccoliths, consequently he considers them intrusives.

§ Presumably dikes would be included also under the term "dolerite."

Haüy[2] used the word in the same sense in 1822, and von Leonhard[3] added that it is usually coarse grained. It is, he said, a basalt whose granularity is visible. At this time, therefore, the extrusive rocks composed of augite and plagioclase were called "basalt" and "dolerite," depending upon their texture. In 1832, von Leonhard[4] inserted between the dense basalt and the coarse dolerite the term "anamesite" (ἀνάμεσος, "in the middle") for the fine granular rocks,

[1] J. F. d'Aubuisson de Voisins, *op. cit.*, p. 148.

[2] L'Abbé Haüy, *op. cit.*, p. 574.

[3] Karl Caesar von Leonhard, *Charakteristik der Felsarten* (Heidelberg, 1823), pp. 118–31, in particular p. 125.

[4] *Die Basalt-Gebilde in ihren Beziehungen zu normalen und abnormalen Felsmassen* (Stuttgart, 1832), Vol. I, pp. 150–51.

indicating that the three are the same except for texture. They were all grouped together by MacCulloch[1] under the old Swedish name "trap," which still is a good field name. Naumann,[2] Senft,[3] Blum,[4] and Zirkel[5] all gave as accessory the mineral titaniferous magnetite, and Sandberger[6] actually separated his dolerite from his basalt by the presence of ilmenite in the former and magnetite in the latter. To Sandberger's divisions objections were made by Bücking,[7] who found that titanium was present in many so-called basalts.

Simply as a coarse-grained basalt, the name "dolerite" is occasionally used in Germany. For example, Zirkel said that "dolerite," "anamesite," and "feldspar-basalt" are only expressions of megascopic structural differences, and we have seen that that is essentially the British use of the term. Rosenbusch did not mention the word in the latest edition of his *Elemente*, and in his *Physiographie* it is spoken of only in connection with Sandberger's attempt to separate it from "basalt."

The confusion in the terms is brought out more clearly by Table I.

[1] John MacCulloch, *System of Geology* (London, 1831), Vol. II, p. 106.

[2] Carl Friedrich Naumann, *Lehrbuch der Geognosie* (Leipzig, 1850), Vol. I, p. 644.

[3] Ferdinand Senft, *Die Felsarten* (Breslau, 1857), pp. 63, 277–81.

[4] J. Reinhard Blum, *Handbuch der Lithologie oder Gesteinslehre* (Erlangen, 1860), pp. 178, 185, 193.

[5] Ferdinand Zirkel, *Lehrbuch der Petrographie* (Bonn, 1866), Vol. II, p. 273.

[6] F. Sandberger, "Über Dolerit und einige Mineralien basaltischer Gesteine," *Neues Jahrb.* (1870), p. 206.

[7] Hugo Bücking, "Über Augitandesite in der südlichen Rhön und in der Wetterau," *TMPM*, Vol. I (1878), pp. 1–3, 14.

THE HOH FORMATION OF WASHINGTON

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ABSTRACT

Three members of the Hoh formation have been delimited: lower, a thick series of soft gray organic Oligocene or Lower Miocene shales of unknown thickness; middle, a soft gray sandstone 150 feet thick, and upper, 2,000 feet of blue-gray sandstone with conglomerate lenses equivalent to the Lower Miocene Temblor of California.

The Hoh formation covers more than half the area of the Olympic Peninsula of the state of Washington. Its rocks have been known for twenty years and the general area has been frequently visited by geologists, yet so uncertain has been its position in the geological column that either the entire formation or members of it have been tentatively placed in the Cretaceous, pre-Cretaceous, Jura, Trias, and even the Carboniferous. The same uncertainty characterizes the information relating to the sequence of its various members.

The unsatisfactory geological information from this region finds explanation, first, in the complicated folding and faulting that characterize the Hoh exposures in the cliffs along the Pacific Coast from Mukkaw Bay to the Raft River, 50 miles to the south; second, in the extreme meagerness of available data inland from the coast, due to the thick mantle of glacial till and the all but impassable forest and underbrush growth; and third, in the complete lack of paleontological data.

During the field season of 1926 a locality was found on the coast, 1 mile north of the Hoh River, where the stratigraphic relationships of at least three of the Hoh members are well exposed. The lowest is a gray shale with a few sandy and conglomerate lenses. The upper 1,000 feet only of these shales are exposed. The thickness is therefore unknown. This member contains much organic matter in the form of vegetable material, Foraminifera, and a few molluscan remains. There is evidence to the effect that this is the oldest Hoh

member exposed anywhere along the coast of the Olympic Peninsula. In this member no fossils were found that are definite age-markers. A *Thyasira bisecta* and a *Phacoides acutilineatus*, however, are evidence that these shales are no lower in the column than Oligocene. A *Crenella*, *Modiolus*, *Diplodonta*, *Solemya*, *Dentalium*, and several other unidentifiable molluscan forms were also found in these shales. In this member oil and gas seeps occur.

The gray shale grades upward into a soft, thinly bedded, light-gray sandstone that has a thickness of 150–200 feet. The bedding is very regular, and many of the individual beds show cross-bedding and also contain much bituminous matter but no fossils.

Lying apparently unconformably upon the gray sandstone are nearly 2,000 feet of massive and bedded sandstone, technically an arkosic graywacke. Within this, and apparently confined to the coast and a few miles inland, are many conglomerate lenses. The sandstone and included conglomerate are very hard and resistant and for the most part form the steep headlands and offshore islands so characteristic of the Washington coast. The sandstone varies from blue gray to blue black and weathers to various shades of tan, buff, and brown near the coast. High in the Olympic Mountains the sandstone is almost black in color owing to the presence of femic minerals and of black organic material. So dense and dark is the rock that isolated unaltered hand specimens have been mistaken for basalt. The weathered surfaces in the higher altitudes are very light or whitish gray. This phenomenon is due to the fact that in the higher altitudes weathering attacks the dark femic minerals much more energetically than the light-colored feldspars and quartz, with the result that the latter minerals persist as bosses on the rock surfaces, while the former retreat into deep pits. In lower altitudes, where organic soil acids are an important factor in weathering, the order of mineral disappearance is reversed.

This sandstone and the gray shale compose the terrain from the coast eastward to the Olympic Mountains, though the shale becomes more sandy toward the east. Near the coast the sandstone is locally quite fossiliferous. Fifty-nine species of molluscs were found. Of these, ten have been described, seven others are very close to described forms, and a few others are evidently identical with forms

from other localities, but as yet undescribed. On the basis of this fossil content, the blue-gray sandstone member of the Hoh formation is correlated with the Clallam formation which occurs along the Strait of Juan de Fuca, with the Empire and Astoria beds of Oregon in part, and with the Kern River Temblor of California, and is therefore Lower Miocene in age.

The underlying members, the gray sandstone and gray shale, may therefore be either pre-Temblor Miocene or Oligocene.

In several localities along the coast a sandy shale is known to occur, though its stratigraphic position is uncertain. This is regularly bedded, greenish gray in color, and quite different from the gray shale member. Its geographic occurrence with the hard sandstone and conglomerate suggest stratigraphic proximity to that member. If such is the case, its position is probably still higher in the column.

REVIEWS

Treatise on Sedimentation. By WILLIAM H. TWENHOFEL and COLLABORATORS. 8vo. Pp. xxv+641, with 61 text figs. Baltimore: Williams & Wilkins, 1926. $7.50.

The work here reviewed is a product of the Committee on Sedimentation of the Division of Geology and Geography of the National Research Council, the culmination of an effort begun in 1920. Many geologists have supplied manuscripts, but the authorship and the editorial work have devolved largely upon Professor Twenhofel.

In the words of the author, sedimentation

> involves a consideration of the sources from which the sediments are derived; the methods of transportation from the places of origin to those of deposition; the methods, agents, and environments of deposition; the chemical and other changes taking place in the sediments from the times of their production to their ultimate consolidation; the climatic and other environmental conditions prevailing at the places of origin, over the regions through which transportation takes place, and in the places of deposition; the structures developed in connection with deposition and consolidation; and the horizontal and vertical variations of the sediments.

The author states that he has tried to make an inventory of existing knowledge relating to sediments, though he makes no pretension of completeness.

The book is a veritable mine of information on the subjects named above and should prove an indispensable aid to every geologist. Its chief advantage is that it gives under each topic, with helpful footnote references, a digest and discussion of the available knowledge relating to that topic and thus provides in a single place information that would otherwise require extended bibliographic search. The references give sufficient basis for more extended studies in many directions. The volume thus becomes, as it was doubtless intended it should be, a logical starting-point for any investigation involving sediments or their complex relationships.

The field of sedimentation is covered in eight chapters, but two of these, which relate, respectively, to products of sedimentation and to structures, textures, and colors of sediments, together comprise nearly two-thirds of the work. The other chapters treat of source, transporta-

tion and deposition, important modifying conditions, the relations of organisms and sediments, the environments of sedimentation, and kindred topics. There is a final chapter on field and laboratory studies of sediments, and at the end of the volume is a List of Authors cited, together with references to the citations, and a good Index.

Among the subjects specially treated most space is allotted to carbonaceous sediments. This section of the volume, which was prepared by David White, is comprehensive, yet concise, and is more adequately illustrated than the other sections. The character and distribution of the materials that enter into carbonaceous sediments are succinctly described from the paleontologic viewpoint, and the biochemical changes that these materials undergo are considered in the light of the environmental conditions under which the sediments were laid down. The deposits formed from woody plants (humic), which contain considerable oxygen, are contrasted with those formed from organic muds, oozes, and slimes (sapropelic), which have relatively more hydrogen. In a suggestive diagram the composition of coal of different ranks is compared, and it is shown that as dynamo-chemical alteration progresses "the ultimate phases of the organic deposits of the humic group are apparently indistinguishable chemically from the ultimate phases of the sapropelic or bituminous deposits."

Limestones, coarser clastics, gypsum, and salt, iron-bearing formations, clays, and silica each occupy more than twenty pages, and phosphates, dolomites, and deposits of manganese take more than ten pages each. Thus such subjects are more fully treated than is generally possible in textbooks.

In the chapter on structural features particular attention is devoted to "ripple mark and its interpretation." The distribution and modes of origin of ripple mark are discussed and a classification is presented. "Each ripple offers some positive information concerning the physical conditions under which it was formed—this information is always valuable and often of crucial significance." A tabulation is made of inferences that can be drawn from ripples, and two examples are given to show how this tabulation may be used in the paleogeographic interpretation of specified formations.

Among the other subjects that receive more than brief statement may be mentioned the following: Transportation of sediments by water and by the atmosphere, the influence of climate on sedimentation, marine and deltaic environmental conditions, concretions, and laboratory studies. To each of these ten or more pages are devoted. Every section of the book

is helpful and informative. The final chapter gives methods of procedure in field and laboratory studies, and might well have been extended.

The authorship of the different sections is generally clear, though it is in part obscured by the compiler's method of condensation or arrangement. It would probably have been more satisfactory to the authors who furnished manuscripts if their contributions could all have been published under their own names, as has been done in some instances.

The illustrations have been reduced to a minimum, and some parts appear to be inadequately illustrated. Probably greater use of sketches or diagrams could have been made to advantage without greatly increasing the cost of the work. The book is substantially bound, and the press-work is attractive. If subsequent editions are prepared they should be more carefully edited. The present work contains many infelicities of expression, misspellings, and typographical errors, which mar the volume though they do not detract from its usefulness.

G. R. MANSFIELD[1]

U. S. GEOLOGICAL SURVEY

[1] Published by permission of the Director, U.S. Geological Survey.

Ore Deposits of the Jerome and Bradshaw Mountains Quadrangles, Arizona. By WALDEMAR LINDGREN, with statistical notes by V. C. HEIKES. *U.S. Geological Survey Bull. 782*, 1926.

This report is written in the usual lucid and concise style of its distinguished author, and is well illustrated. It opens with a consideration of the general geology of the region, as a basis for an adequate understanding of the mineral deposits, and the ores are thoroughly discussed as to type, character, origin, distribution, and value. It contains valuable statistical data on the mining industries of the area compiled by V. C. Heikes.

The formations of this area range from pre-Cambrian to Recent. The oldest pre-Cambrian rocks are schists—recrystallized and metamorphosed sediments—which were intruded, in pre-Cambrian times, by granites, diorites, and diorite porphyries. These are overlaid by Algonkian sediments. Paleozoic sediments, 2,500 feet thick, Cambrian to Permian in age, rest unconformably on the pre-Cambrian. Granodiorite intrusives and rhyolite dikes are assigned to the Cretaceous or early Tertiary. Tertiary (Pliocene) volcanics—flows, necks, and dikes—occur in numerous localities. The lacustrian Verde formation, 1,500 feet thick, is Plio-

cene or possibly Pleistocene in age. Alluvial deposits and terraces occur in the Verde and Lonesome valleys.

A long period of erosion, resulting in peneplanation, was the last recorded episode of pre-Cambrian times. A second enormous erosion intervened between the close of the Paleozoic and the outpouring of the Tertiary volcanics.

The mineral deposits of the area are limited to metals, non-metallic minerals being of little value. A general classification of the ore deposits follows:

Pre-Cambrian ore deposits:
  Pyritic copper deposits in schists
  Magnetite deposits
  Contact-metamorphic deposits
  Gold-quartz veins
  Gold-quartz tourmaline replacement deposits
Later gold and silver veins (Mesozoic? or early Tertiary?):
  Quartz veins carrying gold and silver
  Silver veins:
    Veins with barite gangue
    Veins with quartz gangue

The pyritic copper deposits in the pre-Cambrian schists are economically the most important. Their total output far exceeds the combined output of all other deposits in the district, and is estimated at over $130,000,000. The principal mines are the famous United Verde and United Verde extension. The ores are replacements deposited by solutions of deep origin. Mineralization followed the schistosity, which is preserved in the ore. In form the larger ore bodies are pipelike and the smaller ones lenticular. The great United Verde pipe, 700 feet in diameter, has been mined to a depth of 2,500 feet, and drilling shows it to extend even deeper. It is probable that at least 2,000 feet of it was removed by erosion in pre-Cambrian times. In all, its original vertical extent probably exceeded 5,000 feet.

The first step in the formation of these deposits was the replacement of schist minerals by quartz and, later, by carbonates—calcite, dolomite, ankerite, and some siderite. The sulphide deposition followed in a regular sequence of arsenopyrite, pyrite, sphalerite, chalcopyrite, galena, and tennantite, the later sulphides replacing the earlier, an order of deposition which has been prevalent in general in all of the sulphide deposits of the region. Some gangue was of course deposited with the sulphides. Plutonic igneous rocks are not invariably present near the pyritic copper

deposits and when present show considerable variety. The similarity of these deposits over considerable areas implies, however, some common deep-seated source, probably igneous, for the mineralizing solutions. The probable source is some phase of the Bradshaw granite batholith that at depth underlies the whole pre-Cambrian complex.

The ores worked are in the main primary, erosion having been so active in recent geologic times as to afford little opportunity for thorough oxidation and for sulphide enrichment. Of unique interest, however, is the presence in the United Verde extension of buried zones of oxidation and enrichment lying beneath the cover of Paleozoic rocks and developed at the time of pre-Cambrian peneplanation. The oxidized zone is 300–400 feet deep, and the chalcocite zone, 400–600 feet deep, constitutes one of the largest known bodies of chalcocite ore. In 1916 it produced roundly $10,000,000 worth of ore. At the top of the chalcocite zone a distinct enrichment in silver occurs. Much of the ore shipped averaged 27 per cent of copper.

The pyritic copper ores of this region find their closest analogues in the deposits of Rio Tinto in Spain and of Rammelsberg in Sweden.

The magnetite deposits and the single contact metamorphic deposit are of little or no economic importance. The pre-Cambrian quartz veins carrying gold, or gold and silver, are of minor economic importance and show no exceptional geologic features.

In the Bradshaw Mountains quadrangle, but not in the Jerome quadrangle, occur a large number of gold and silver veins of probable Mesozoic or early Tertiary age. They are fissure veins whose walls show hydrothermal alteration with the development of sericite and carbonates. Base metals are valuable only as by-products. Their productiveness has been very small as compared with the great pre-Cambrian pyritic copper deposits.

E. S. B. AND A. H. S.

Ice Ages—Recent and Ancient. By A. P. COLEMAN. New York: The Macmillan Co., 1926. Pp. xliii+296; 51 figs.; 8 maps.

This book deals with the brief episodes of cold usually passed over lightly or even unmentioned in books on geology—the "short spells of trial and stress" which "meant far more to the development of the world's inhabitants than all the long periods of ease and sloth when the earth was a hot-house."

Attention is called to the striking fact that in almost all the major

divisions of geological time ice-action has been suspected or proved, and that at four times—the Pleistocene, the Permo-Carboniferous, the early Cambrian or late pre-Cambrian, and the Huronian—glaciation was on so broad a scale that glaciers of the continental type must have been at work, and "hence there must have been a very serious lowering of temperature in the areas affected and probably in the whole world."

As a background for a satisfactory understanding of the glacial deposits of earlier ice sheets, the mode of operation and geological results of modern glaciers are discussed briefly.

The Pleistocene ice age is described chiefly with regard to those features which throw light on more ancient, and therefore less completely recorded, glaciations. In dealing with the Pleistocene glaciation of North America, the author includes the chief facts about the Cordilleran, Keewatin, and Labradorean ice sheets, and refers to the important question of the occurrence of interglacial epochs. In his reference on page 21 to the classification of the Pleistocene deposits of the Mississippi Valley, which recognizes five glacial and four interglacial epochs, the names Sangamon and Yarmouth given for the second and third interglacial epochs, respectively, should be transposed. Pleistocene glaciation in regions other than North America, the results of glaciation including the effects of Pleistocene glaciation on life, and the probable duration of Pleistocene time are considered. It is an interesting fact that the area of Pleistocene glaciation almost exactly covered the parts of the earth which escaped glaciation at the end of the Paleozoic.

The best proofs of ancient glaciation are consolidated tills (tillites) with their soled bowlders and striated stones. Knowledge of the extent and severity of the far-off glaciations is dependent on the accident of preservation of the original tillites in places open to the study of the geologist; and "that we have any record of them at all is astonishing."

In discussing Mesozoic and pre-Pleistocene Cenozoic glaciation, particular emphasis is given to the evidence of Eocene glaciation and its effect upon life. "By a comparatively small change of climate, with cooler winters than reptiles could endure, the life of the world was turned in a wholly new direction, favoring the mammals and culminating in man himself."

Although glaciation is strongly suspected or proved in all of the great subdivisions of the Paleozoic, it is the glaciation of the Permo-Carboniferous which is of most intense interest. There is unmistakable evidence that near the end of the Paleozoic great ice sheets existed on low ground within the tropics on two continents and not far from the tropics on two others.

This is the "most tremendous ice age on record" and hence is described in greater detail than the others. The deposits of India, Africa, Australia, and South America were studied at first hand by the author. In describing the late Paleozoic glaciation of New South Wales, in Australia, he emphasizes the enormous thickness of the glacial deposits, including marine deposits, and states that there is distinct evidence of three glacial and two very long interglacial epochs. "These are the most extensive interglacial formations known in the world and must have required hundreds of thousands and even millions of years for their deposit." The Dwyka tillite of South Africa "is twice as thick as the greatest development of the Pleistocene complex of till and interglacial deposits of North America."

Evidences of Middle and Early Paleozoic glaciation and pre-Cambrian glaciation are presented. The descriptions of glaciation of the Huronian and earlier time make intensely interesting reading. In the case of the Huronian, the area of glaciation is so great that one must assume a very important refrigeration, one to be classed among the first four in severity. "Now it appears probable that the Pre-Cambrian was the coldest part of the earth's history, with glaciers at work within every one of its main subdivisions." "The finding of the evidences of ancient glaciation has revolutionized our ideas as to the origin and history of the world and has rendered improbable the theory which was accepted by both astronomers and geologists a generation ago as the natural starting point in the evolution of the planet."

The causes of glaciation are discussed. The author presents the principal geological, atmospheric, and astronomic theories which have been advanced to explain glaciation. He points out some of the features which must be accounted for in testing the validity of any theory which attempts to account for ice ages. All theories thus far put forward fail in some respects to solve the problems which are involved in explaining ice ages. The author after his many years of study of glaciation feels incompetent to propose a satisfactory theory of his own, but he expresses the opinion that the final solution of the complicated problems must come from some combination of astronomic, geologic, and atmospheric conditions.

Dr. Coleman has been an earnest student of glacial phenomena for many years. He has examined critically more of the areas of the world where evidences of ancient glaciation are known than perhaps any other geologist has ever done. His book is one of the fruits of his life. It should be read not only by persons with special interests in glaciers, recent and ancient, but by laymen, all of whom would derive profit and pleasure in

reading this fascinating story of ice ages which "have occasioned far-reaching and salutary changes in the world's population as judged by the human point of view." The book is written in simple, concise language. All evidence was weighed carefully, well organized, and written so clearly that the reader gets all essential facts and interpretations without unnecessary details. From an extensive literature with which the author shows thorough familiarity there is given at the end of each chapter a very useful bibliography. A few well-chosen illustrations and maps add to the worth of this excellent book.

G. F. KAY

Pennsylvanian Flora of Northern Illinois. By A. C. NOÉ. *Illinois State Geological Survey Bull. 52*, 1925. Pp. 18; pls. 45.

This, on the fossil flora of No. 2 coal bed of District 1 in northern Illinois, is the first of a series of papers figuring and describing in detail the Pennsylvanian flora of Illinois. It is the outgrowth of the program of fundamental scientific studies by the Illinois State Survey. The orders, genera, and species are classified and briefly described in non-technical language. The *Bulletin* is devoted chiefly to plates of beautiful photographic reproductions of fossil leaves, stems, and fructifications. It will serve as a very important contribution to paleobotanical and stratigraphic correlation. Technical descriptions of both known and new species are reserved for a monograph on the Pennsylvanian flora of the Illinois, Kentucky, and Indiana coal basin now in preparation.

P. M.

An Upper Ordovician Fauna from the Rocky Mountains, British Columbia. By ALICE E. WILSON. Contributions to Canadian Palaeontology, *Canadian Geol. Survey Bull. 44*, Geol. Ser. No. 46 (1926).

Under the foregoing title a number of species from British Columbia have been described. Additions to our knowledge of the faunas of the western Paleozoic are always welcome, particularly from such little-known areas as the Canadian Rockies. It is unfortunate, in the present instance, that the studies have been based for the most part on indifferent material, which has apparently been collected with small regard for stratigraphic position. I have myself collected from most of the localities furnishing material for this paper, including the Stoddard Creek and Harrogate sections, and wish to make such corrections as are immediately

obvious from an examination of the paper alone in conjunction with material at hand.

It may be well first to state that the Upper Ordovician fauna is found in the Beaverfoot formation, which is overlain by the Silurian Brisco formation. The Ordovician fauna may be of Richmond age or may be somewhat earlier. The Silurian fauna is almost certainly not older than Niagaran. For this reason it seems highly improbable that there should be an intermingled Silurian and Ordovician fauna as suggested in this paper. Recently Walker[1] has assumed the same relationship of the Silurian and Ordovician faunas. In the present paper this transitional fauna seems primarily to be based on two collections, one from the Stoddard Creek section and one from Harrogate.

In both instances I am confident that the supposed intermingling of the faunas has been due to mixing of material collected from the two formations. In the Stoddard Creek section, the geological structure is made somewhat complex by series of longitudinal and cross faults, the latter often giving considerable offsets in the outcrops along the strike. If collections from individual outcrops had been kept separate, probably no confusion would have resulted. The Harrogate section, so far as these formations are concerned, is simple; but loose material from the overlying Silurian must have been collected along with the Ordovician fossils, or else the line between the Ordovician and Silurian was not recognized, and collecting was carried on up into the Silurian. Of the species described, the following may safely be ascribed to the Silurian:

Streptelasma fragile n. sp.
Plasmadictyon irregulare gen. and sp. nov.
Syringopora columbiana n. sp.
Favosites cf. favosus (Goldfuss)

The following two species may doubtfully be referred to the Silurian:

Halysites pulchellus n. sp.
Halysites cylindricus n. sp.

The new genus *Plasmadictyon* listed above seems to be identical with a coral I have from the same locality and does not seem to differ from typical *Alveolites*.

Most of the Ordovician material is in too poor a state of preservation to warrant comparison with described species and varieties. It may be noted, however, that *Syringopora burlingi* n. sp. is almost certainly a badly preserved *Calapoecia*. The genus *Syringopora* then still remains of post-Ordovician age. *Diphyphyllum? halysitoides* n. sp. bears a striking

[1] J. F. Walker, "Geology and Mineral Deposits of Windermere Map-area, British Columbia, *Geol. Survey Canada Mem. 148* (1922).

resemblance to *Columnaria calicina* Nicholson or possibly together with *Diphyphyllum? primum* n. sp. may be referable to *Palaeophyllum*. The latter species should be compared with *Palaeophyllum stokesi* (E. and H.). Of the new brachiopod genus *Petroria*, Miss Wilson says: "Its exact affinities cannot be found until more and better interiors have been procured." Because of the obviously advanced state of silicification of the specimens and their imperfect character, one cannot but wonder why a new genus was required for their reception, when the form seems to have all the earmarks of *Plectambonites*.

EDWIN KIRK.[1]

U.S. GEOLOGICAL SURVEY

A Résumé of Arizona Geology. By N. H. DARTON. *University of Arizona Bull. No. 119*, Geol. Series No. 3 (1925). Pp. 298; pls. 74; figs. 105.

This bulletin is an excellent summary of the stratigraphic and structural geology of Arizona, compiled from previously published data and supplemented with much new material gathered by the author in a reconnaissance of the state during 1919 to 1922. The résumé is in two parts. Under "stratigraphic geology" the general characteristics of the formations of each period are briefly summarized, followed by more detailed accounts of the outcrops in various districts. Numerous stratigraphic sections and fossil lists are given in condensed form with all available new light on correlation and classification. For those districts on which published data are scarce or lacking, the author has supplied more complete descriptions. In the second part, entitled "descriptive geology," the topography and structure of the various districts are discussed according to counties. The text is profusely illustrated with photographs and geologic maps. Over 160 structure sections are reproduced.

The work is not intended as a monographic report on Arizona geology; ore deposits are not discussed; and it is purposely limited to the above outline. With its concise and systematic summary of present known data and the large number of sections and geologic maps, the bulletin will prove a most valuable reference work for anyone interested in the geology of Arizona. Unfortunately there is no index; but this is not a serious omission, as the subheadings in the Table of Contents and the general plan of presentation make it easy to refer quickly to any district. References to the published literature are given in numerous footnotes.

J. T. STARK

[1] Published by permission of the director, U. S. Geological Survey.